# APPENDIX A: S-PARAMETERS OF TANDEM CONNECTED COUPLERS

## A.1 Introduction

For the realisation of phase shifters of nominal phase shift value higher than about 30°, the coupling requirements of a single coupler becomes too tight. By tandem connection of two or more couplers, any phase shift can be achieved. This appendix describes the properties of tandem connection of couplers, by using simple matrix manipulation.

## A.2 *S*-Parameter Calculations

Standard theory of couplers may be expanded to derive the *S*-parameter nature of identical tandem-connected couplers. For a single coupler, the *S* parameter matrix equation can be defined as

$$\begin{bmatrix} b_1 \\ b_2 \\ b_3 \\ b_4 \end{bmatrix} = \begin{bmatrix} 0 & f_1 & 0 & f_2 \\ f_1 & 0 & f_2 & 0 \\ 0 & f_2 & 0 & f_1 \\ f_2 & 0 & f_1 & 0 \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \end{bmatrix} . \tag{A1}$$

Where the coupling- and transmission coefficients are defined as

$$f_1 = j\ k(f) \qquad \text{The coupling coefficient ,} \tag{A2}$$

$$f_2 = \sqrt{1 - k^2\ (f)} \qquad \text{The transmission coefficient .} \tag{A3}$$

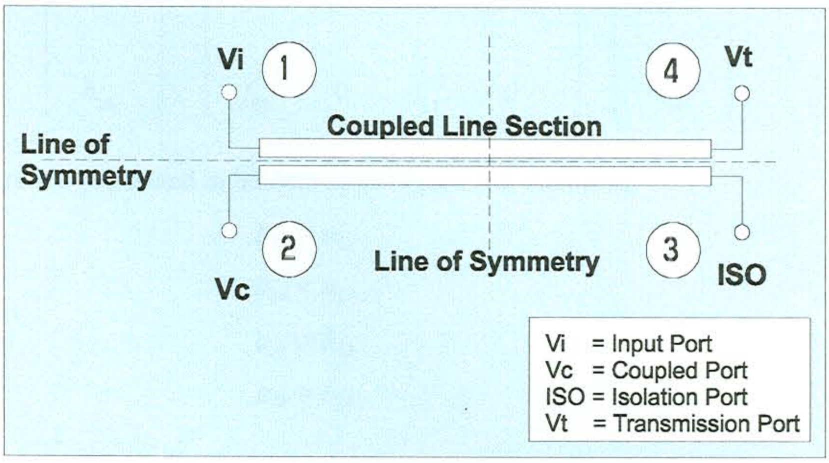


**Figure A1 : Definition of a single symmetric coupler**

The definition of such a symmetric coupler is shown in Figure A1. When excited from port (1) and with all other ports terminated, *a2 = a3 = a4 = 0.*

Then, from matrix A1, it is concluded that:

$$b_2 = f_c a_1 \quad b_1 = b_3 = 0\,, \qquad \text{(A4)}$$
$$b_4 = f_t a_1 \;.$$

Then for the individual couplers, the two matrixes can be defined as

$$\begin{bmatrix} b_{11} \\ b_{12} \\ b_{13} \\ b_{14} \end{bmatrix} = \begin{bmatrix} 0 & f_{11} & 0 & f_{12} \\ f_{11} & 0 & f_{12} & 0 \\ 0 & f_{12} & 0 & f_{11} \\ f_{12} & 0 & f_{11} & 0 \end{bmatrix} \cdot \begin{bmatrix} a_{11} \\ a_{12} \\ a_{13} \\ a_{14} \end{bmatrix}, \qquad \text{(A5)}$$

$$\begin{bmatrix} b_{12} \\ b_{22} \\ b_{23} \\ b_{24} \end{bmatrix} = \begin{bmatrix} 0 & f_{21} & 0 & f_{22} \\ f_{21} & 0 & f_{22} & 0 \\ 0 & f_{22} & 0 & f_{21} \\ f_{22} & 0 & f_{21} & 0 \end{bmatrix} \cdot \begin{bmatrix} a_{21} \\ a_{22} \\ a_{23} \\ a_{24} \end{bmatrix}. \qquad \text{(A6)}$$

The two couplers are connected in tandem as in Figure A2, therefore

$$b_{21} = a_{12}\,, \qquad \text{(A7)}$$
$$b_{14} = a_{23}\,, \qquad \text{(A8)}$$
$$a_{21} = b_{12}\,, \qquad \text{(A9)}$$
$$a_{14} = b_{23}\,. \qquad \text{(A10)}$$

The matrixes can be written in equation form as

$$b_{11} = a_{12}f_{11} + a_{14}f_{12} \; , \qquad \text{(A11)}$$

$$b_{12} = a_{11}f_{11} + a_{13}f_{12} \; , \qquad \text{(A12)}$$

$$b_{13} = a_{12}f_{12} + a_{14}f_{11} \; , \qquad \text{(A13)}$$

$$b_{14} = a_{11}f_{12} + a_{13}f_{11} \; , \qquad \text{(A14)}$$

$$b_{21} = a_{22}f_{21} + a_{24}f_{22} \; , \qquad \text{(A15)}$$

$$b_{22} = a_{21}f_{21} + a_{23}f_{22} \; , \qquad \text{(A16)}$$

$$b_{23} = a_{22}f_{22} + a_{24}f_{21} \; , \qquad \text{(A17)}$$

$$b_{24} = a_{21}f_{22} + a_{23}f_{21} \; . \qquad \text{(A18)}$$

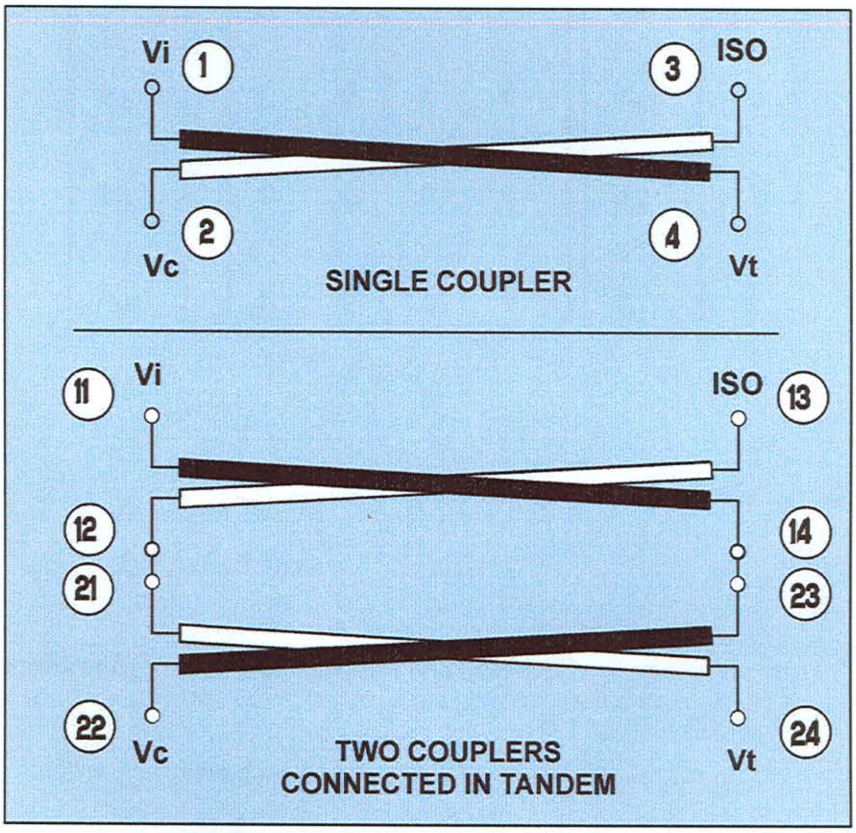


**Figure A2 : Tandem connected couplers**

Substituting

(A7) in (A15): $a_{12} = a_{22}f_{21} + a_{24}f_{22}$ , (A19)

(A9) in (A12): $a_{21} = a_{11}f_{11} + a_{13}f_{12}$ , (A20)

(A8) in (A14): $a_{23} = a_{11}f_{12} + a_{13}f_{11}$ , (A21)

(A10) in (A17): $a_{14} = a_{22}f_{22} + a_{24}f_{21}$ . (A22) and

(A19) and (A22) in (A11): $b_{11} = [f_{11}f_{21} + f_{12}f_{22}]\, a_{22} + [f_{11}f_{22} + f_{12}f_{21}]\, a_{24}$ , (A23)

(A19) and (A22) in (A13): $b_{13} = [f_{21}f_{12} + f_{11}f_{22}]\, a_{22} + [f_{11}f_{21} + f_{21}f_{22}]\, a_{24}$ , (A24)

(A20) and (A21) in (A16): $b_{22} = [f_{11}f_{21} + f_{12}f_{22}]\, a_{11} + [f_{11}f_{22} + f_{12}f_{21}]\, a_{13}$ , (A25)

(A20) and (A21) in (A18): $b_{24} = [f_{11}f_{22} + f_{12}f_{21}]\, a_{11} + [f_{11}f_{21} + f_{12}f_{22}]\, a_{13}$ . (A26)

Equations (A23) to (a26) can be written in martrix form. Therefore, the tandem component matrix is as

$$\begin{bmatrix} b_{11} \\ b_{22} \\ b_{13} \\ b_{24} \end{bmatrix} = \begin{bmatrix} 0 & f_1 & 0 & f_2 \\ f_1 & 0 & f_2 & 0 \\ 0 & f_2 & 0 & f_1 \\ f_2 & 0 & f_1 & 0 \end{bmatrix} \begin{bmatrix} a_{11} \\ a_{22} \\ a_{13} \\ a_{24} \end{bmatrix} . \quad \text{(A27)}$$

where

$$f_1 = f_{11}f_{21} + f_{12}f_{22} \ , \quad \text{(A28)}$$

$$f_2 = f_{11}f_{22} + f_{12}f_{21} \ . \quad \text{(A29)}$$

Applying the transform $K(f) = sin\ \phi$ to equations (A2) and (A3)

$$f_{11} = j\ sin\ \phi_1 \ , \quad \text{(A30)}$$

$$f_{12} = cos\ \phi_1 \ , \quad \text{(A31)}$$

$$f_{21} = j\ sin\ \phi_2 \ , \quad \text{(A32)}$$

$$f_{22} = cos\ \phi_2 \ . \quad \text{(A33)}$$

Substituting equations (A30) to (A33) in (A28) and (A29) yields

$$f_1 = j\ sin\ (\phi_1 + \phi_2) \ , \quad \text{(A34)}$$

$$f_2 = cos\ (\phi_1 + \phi_2) \ . \quad \text{(A35)}$$

## A3. Conclusion

From the results it is clear that the coupling angles of tandem-connected couplers can be added directly. The ripple angles can be added too. The phase shifter design can therefore be simplified by equally dividing the phase shift between the couplers, and by having to design only a single coupler, since all stages are identical.

# APPENDIX B: SYMMETRICAL PHASE SHIFTER PERFORMANCE ENHANCEMENT

## B1. Introduction

Manufacturing tolerances usually degrade the performance of a component. It is assumed that the via interconnections in the splitter, or any other non-ideal effect, can be modelled as a small series parasitic inductance. This section demonstrates the valuable advantage to be gained by introducing symmetry to the phase shifter. It will be shown that particularly the via interconnection may severely degrade the phase shift performance of an asymmetric phase shifter. The symmetric phase shifter fully compensates for these effects.

## B2. Asymmetric Phase Shifter Performance

To illustrate how symmetric construction decreases phase shift error, let us assume that the via can be represented by a small inductance $L$, of impedance $E$, in one line.

$$E = 2\pi f L \tag{B1}$$

The voltage transmission, $V_0$, over a series inductance $jE$ can be derived:

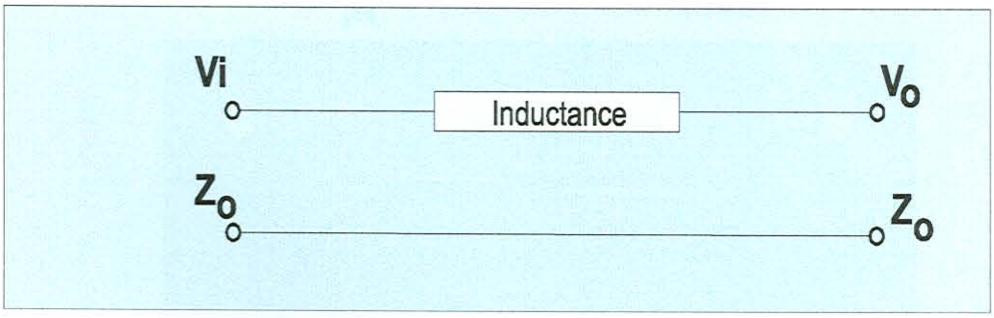


**Figure B1 : Model of a single via through connection**

$$V_0 = V_i - jE\left[\frac{V_i}{Z_0 + jE}\right] , \tag{B2}$$

$$V_0 = V_i\left[\frac{1}{1 + je}\right] \qquad \text{where} \qquad e = E/Z_0 \ . \tag{B3}$$

Ignoring second-order effects ($e^2 << 1$), equation (B3) becomes

$$V_0 \approx V_i\ [1 - j\,e] \quad . \tag{B4}$$

For the asymmetric phase shifter, the transfer function can be derived as

$$B/A = (1 - j\,e)\,f_c + f_T \quad . \tag{B5}$$

Using definition (2.10) and (2.11)

$$f_c = j \sin \phi \quad , \tag{B6}$$

$$f_T = \cos \phi \quad . \tag{B7}$$

By neglecting second order effects, we simplify the equation (B5) and find

$$B/A \approx \sqrt{1 + e \sin 2\phi}\quad e^{\left(j\, atan\left[\frac{\tan \phi}{1 + e \tan \phi}\right]\right)} \quad . \tag{B8}$$

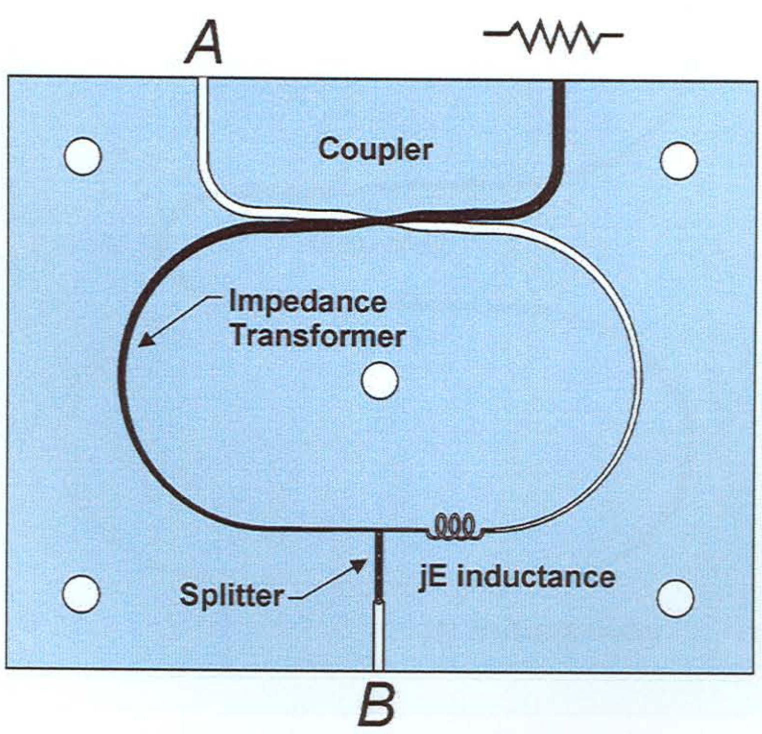


**Figure B2 : The asymmetric phase shifter**

Since the amplitude distortion is negligible ($e$ is small) it can be seen that for large values of $\phi$ the phase therm has a large frequency-dependent error term. This can not be compensated for by simple means.

## B3. Symmetric Phase Shifter Performance

Applying the same error symmetrically, the transfer function of the symmetric phase shifter becomes:

$$B/A \approx (1 - je)\left[ f_c + f_T - \frac{e^2}{2\,(1 - j\,e)} \cdot f_c \right] . \tag{B9}$$

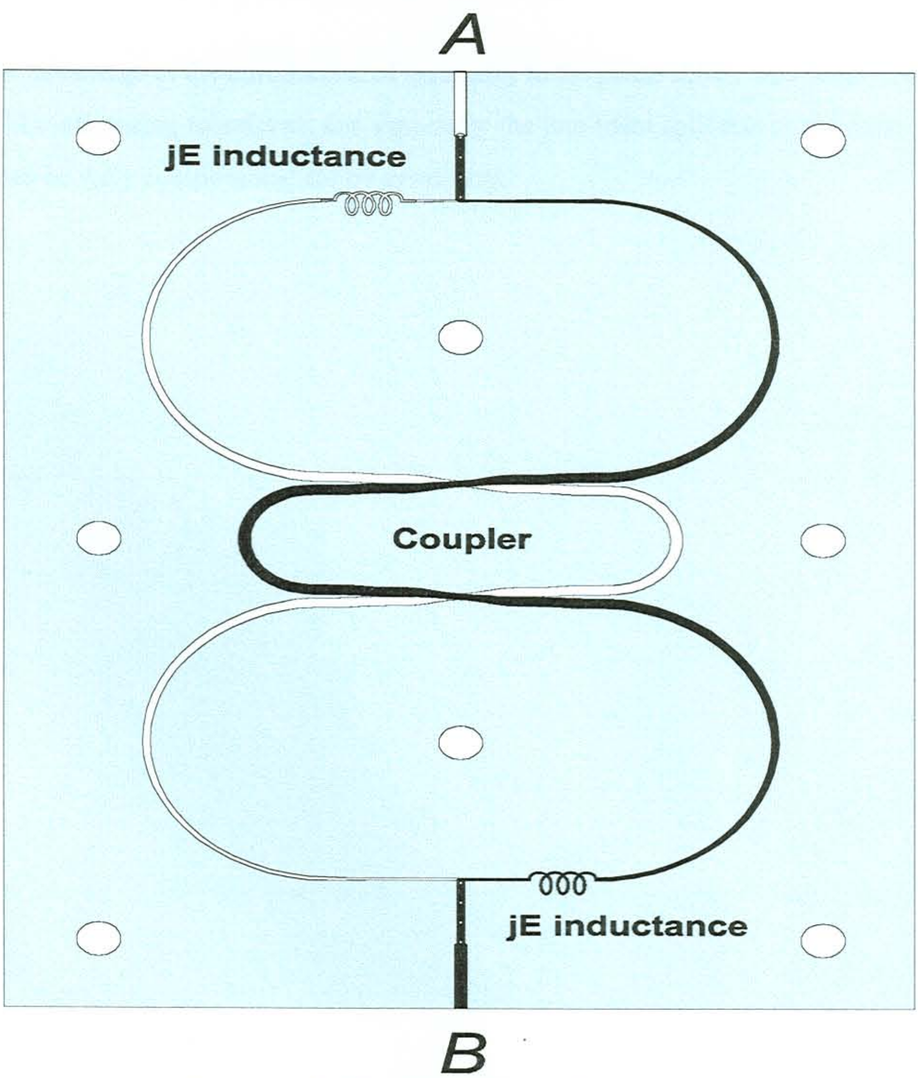


**Figure B3 : The symmetric phase shifter**

Ignoring second-order terms,

$$B/A \approx (1 - j\,e)\,(f_c + f_T) \quad , \qquad \text{(B10)}$$

$$\approx 1.e^{-j\,\arctan(e)} \,.\, e^{j\,\phi} \quad . \qquad \text{(B11)}$$

The amplitude is virtually undistorted and a small additive phase delay of *arctan (e)* is introduced. This can be fully compensated for by a short line added to the reference line.

## B4. Conclusion

The valuable advantage of the introduction of symmetry to the phase shifter was demonstrated in this appendix. Manufacturing tolerances, and especially the non-ideal split due to the finite number of vias used, can be fully compensated for by symmetry.

# APPENDIX C: REFLECTION ANALYSIS OF A SYSTEM OF MULTIPLE IDENTICAL VIAS

## C1. Introduction

To accurately determine the odd mode *S*-parameters of the splitter, it is necessary to determine the properties of a system of any number of equally spaced vias in a medium of odd-mode impedance. It is assumed that only the vias contribute to reflections in the structure. Standard S-parameter theory combined with the well-known reflectogram is used to add all transmission and reflection contributions in the structure. There terms form an arithmetic series which can be written in closed form.

## C2. Reflectogram Analysis

Firstly, the reflection and transmission properties of a single via in odd mode medium is determined. The results will be used for multiple via analysis.

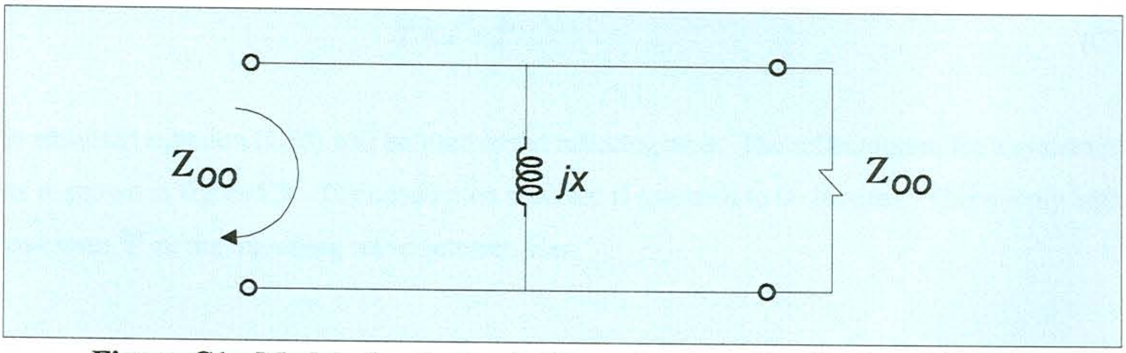


**Figure C1 : Model of a single via through connection in the odd mode**

The reflection coefficient is therefore

$$\Gamma = \frac{jX \,//\, Z_{00} - Z_{00}}{jX \,//\, Z_{00} + Z_{00}} \;,$$

$$= \frac{-1 + 2jx}{1 + 4x^2} \qquad \text{where} \qquad x = \frac{X}{Z_{00}} \;. \tag{C1}$$

For lossless networks, energy conservation applied to *S*-parameters yield the following general equations

$$\sum_{j=1}^{2} |S_{ij}|^2 = 1 \;, \tag{C2}$$

$$\text{and} \sum_{j=1}^{2} S_{jm} \,.\, S^*_{jn} = 0 \;; \qquad m \neq n \;. \tag{C3}$$

For two-port networks, equations (C2) and (C3) can be written as

$$|\Gamma|^2 + |T|^2 = 1 \ , \tag{C4}$$

$$\text{and} \qquad \Gamma T^* + T \Gamma^* = 0 \ . \tag{C5}$$

$$\text{let} \qquad \Gamma = A + jB \ , \tag{C6}$$

$$T = a + jb \ . \tag{C7}$$

Substituting equations (C6) and (C7) into (C4) and (C5), and solving in terms of A and B, yields

$$T = \left[ -\frac{B}{A} + j \right] \sqrt{\frac{1 - (A^2 + B^2)}{1 + (B/A)^2}} \ , \tag{C8}$$

$$= \frac{4x^2 + j\,2x}{1 + 4x^2} \ . \tag{C9}$$

Therefore:

$$T = 1 + \Gamma \ . \tag{C10}$$

The resultant equation (C10) will be used in the reflectograms. The reflectogram for a system of 2 vias is shown in figure C2. The conduction medium is assumed to be lossless. This simply adds a phase term $\Psi$ to the travelling wave between vias.

$$\text{Let} \qquad \Psi = e^{-j\theta} \ . \tag{C11}$$

Adding reflection and transmission terms, the following series can be written from Figure C2:

$$\Gamma_2 = \Gamma + T^2 \Psi^2 \Gamma + T^2 \Psi^4 \Gamma^3 + T^2 \Psi^6 \Gamma^5 + T^2 \Psi^8 \Gamma^7 + \ldots \tag{C12}$$

$$= \Gamma + \frac{T^2 \Psi^2 \Gamma}{(1 - \Psi^2 \Gamma^2)} \ , \tag{C13}$$

$$T_2 = T^2 \Psi + T^2 \Psi^3 \Gamma^2 + T^2 \Psi^5 \Gamma^4 + T^2 \Psi^7 \Gamma^6 + \ldots \tag{C14}$$

$$= \frac{T^2 \Psi}{(1 - \Psi^2 \Gamma^2)} \ . \tag{C15}$$

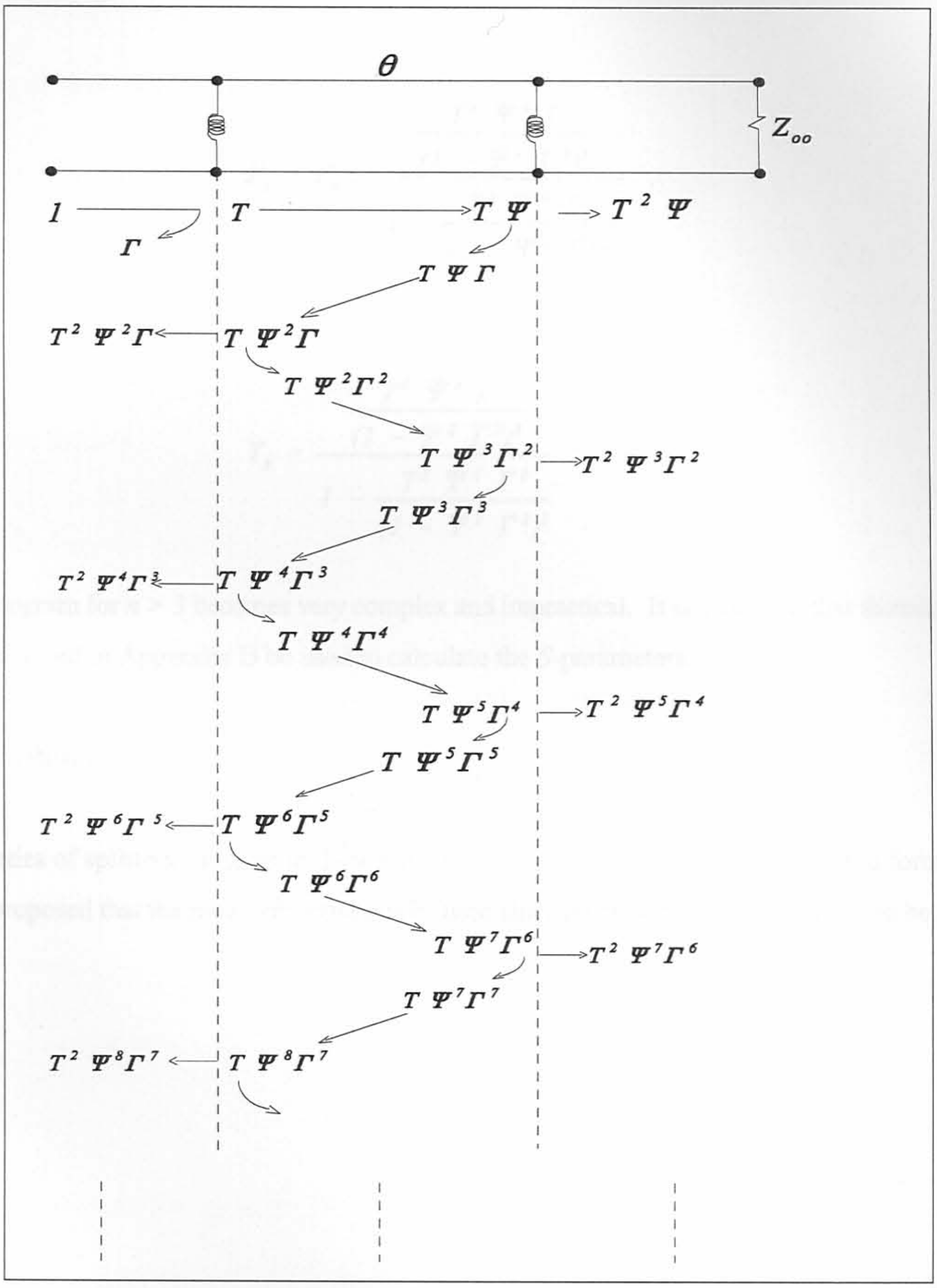


**Figure C2 : Reflectogram of a system of two via interconnections**

The reflectogram is not overly complicated, and identifying the series is fairly straight forward. Increasing the number of vias beyond three complicates matters.

It can be shown that

$$\Gamma_3 = \Gamma_2 + \frac{\dfrac{T^4\ \Psi^4\ \Gamma}{(1-\Psi^2\ \Gamma^2)^3}}{1-\dfrac{T^2\ \Psi^4\ \Gamma^2}{(1-\Psi^2\ \Gamma^2)^2}}\ , \tag{C16}$$

$$T_3 = \frac{\dfrac{T^4\ \Psi^4\ \Gamma}{(1-\Psi^2\ \Gamma^2)^3}}{1-\dfrac{T^2\ \Psi^4\ \Gamma^2}{(1-\Psi^2\ \Gamma^2)^2}}\ . \tag{C17}$$

This reflectogram for $n > 3$ becomes very complex and impractical. It is proposed that the recursion equations derived in Appendix D be used to calculate the *S*-parameters.

## C3. Conclusion

The properties of splitters using up to three vias in the odd mode were derived in closed form. For $n > 3$ it is proposed that the recursion equations be used since no closed-form solution could be found.

# APPENDIX D: RECURSION EQUATIONS OF A SYSTEM OF MULTIPLE IDENTICAL VIAS

## D1. Introduction

To accurately determine the odd mode *S*-parameters of the splitter, it is necessary to determine the properties of a system of any number of equally spaced vias in a medium of odd-mode impedance. Standard *S*-parameter theory combined with the reflectogram is used to calculate recursion equations for a periodic structure of $n$ identical vias spaced equally in BCS. The closed-form equations of up to three vias were calculated in Appendix C. For any number of vias $n = 1\ to\ \infty$, the recursion equations can be used.

## D2. Reflectogram Analysis

The assumptions used and results obtained in Appendix C will be built on. The reflectogram for determining the recursion equations is shown in figure D1. Summing the relevant terms, we find

$$\Gamma_{n+1} = \Gamma + T^2 \Gamma\ \Psi^2 \Gamma_n + T^2 \Psi^4 \Gamma \Gamma_n + T^2 \Psi^6 \Gamma^2 \Gamma^3_n + T^2 \Psi^8 \Gamma^3 \Gamma_n{}^4 + \ldots, \tag{D1}$$

and

$$T_{n+1} = T \Psi T_n + T \Psi^3 \Gamma \Gamma_n T_n + T \Psi^5 \Gamma^2 \Gamma^2_n T_n + T \Psi^7 \Gamma^3 \Gamma_n^3 T_n + \ldots. \tag{D2}$$

These terms can be written in closed form as

$$\Gamma_{n+1} = \frac{T^2\ \Psi^2\ \Gamma_n}{1 - \Psi^2\ \Gamma \Gamma_n} + \Gamma\ , \tag{D3}$$

$$T_{n+1} = \frac{T\ \Psi\ T_n}{1 - \Psi^2\ \Gamma \Gamma_n}\ . \tag{D4}$$

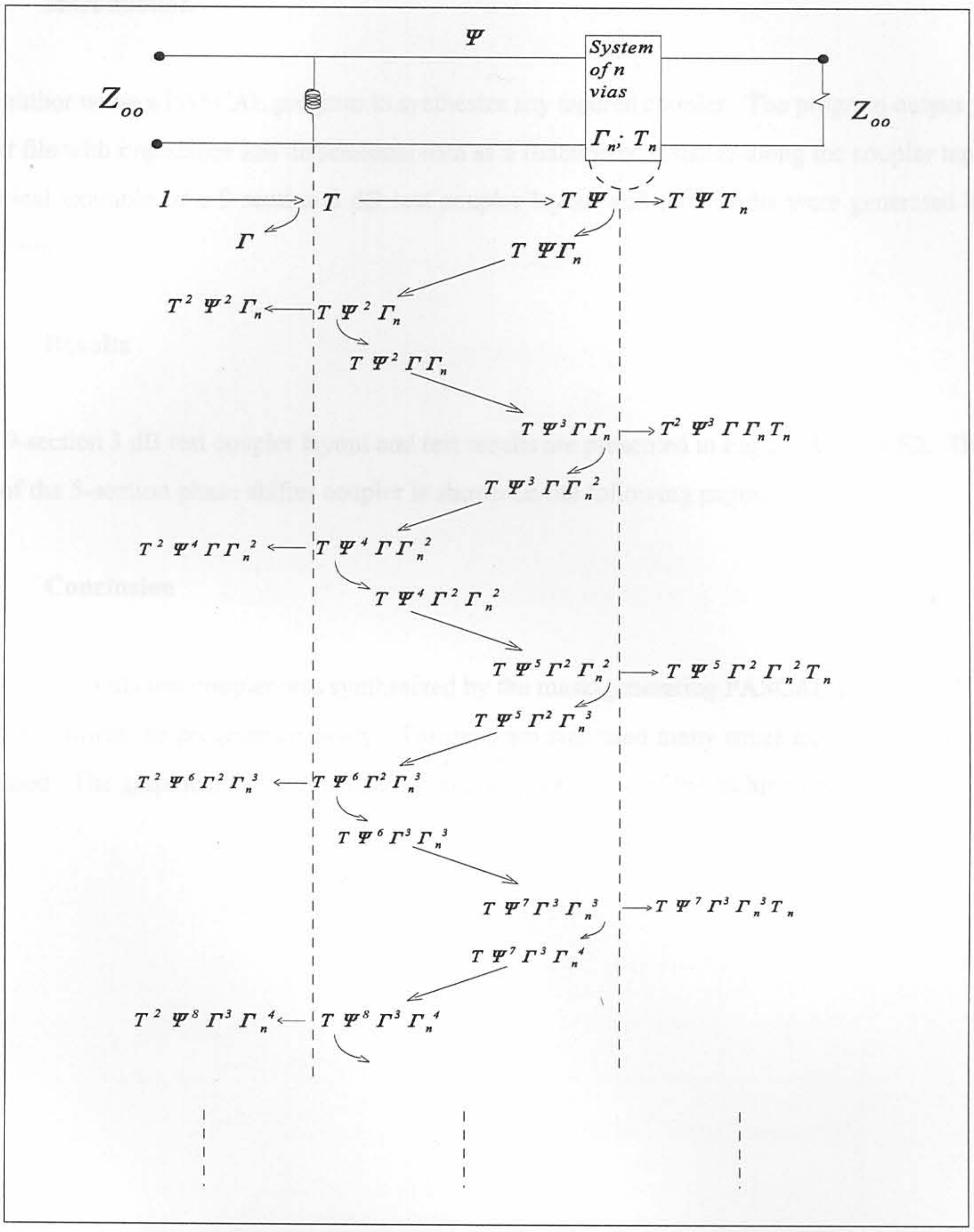


**Figure D1 : Reflectogram for the derivation of the recursion equations**

## D3. Conclusion

The recursion equations of reflection and transmission properties of a system of any number of identical vias in odd-mode impedance have been derived. These equations yield the same results as the closed-form equations for $n$ = 1, 2, 3 as derived in Appendix C.

# APPENDIX E: COUPLER SYNTHESIS RESULTS

## E1. Introduction

The author wrote a PASCAL program to synthesize any tapered coupler. The program output yields a text file with impedance and dimensional data as a function of distance along the coupler taper. A practical example of a 9-section 3 dB test coupler layout and test results were generated by the program.

## E2. Results

The 9-section 3 dB test coupler layout and test results are presented in Figures E1 and E2. The text file of the 5-section phase shifter coupler is shown on the following pages.

## E3. Conclusion

A 9-section 3 dB test coupler was synthesized by the mask-generating PASCAL program. The test results confirm the program accuracy. The program was used many times and good results were obtained. The graphical file was used to create the photomask of the etching process.

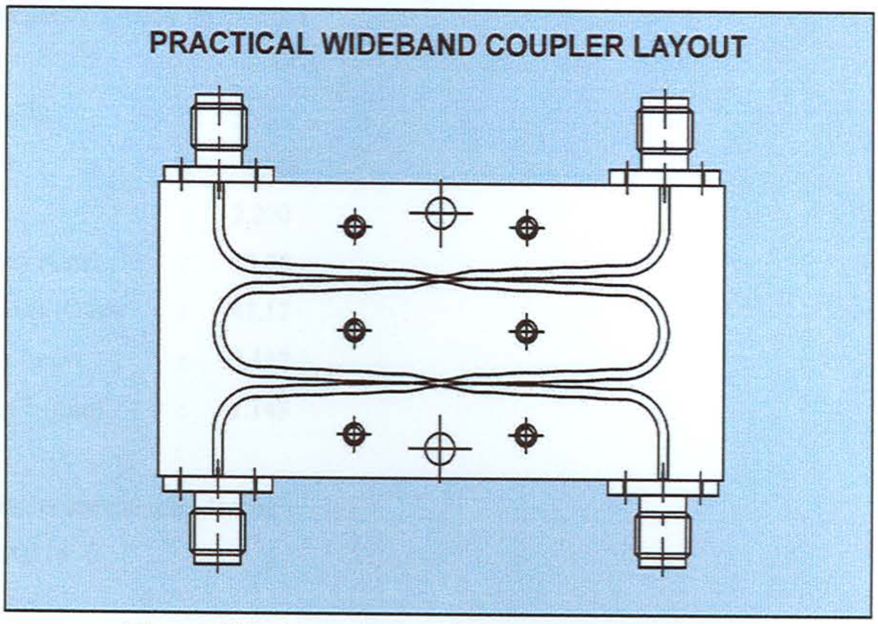


**Figure E1 : Practical wideband coupler layout**

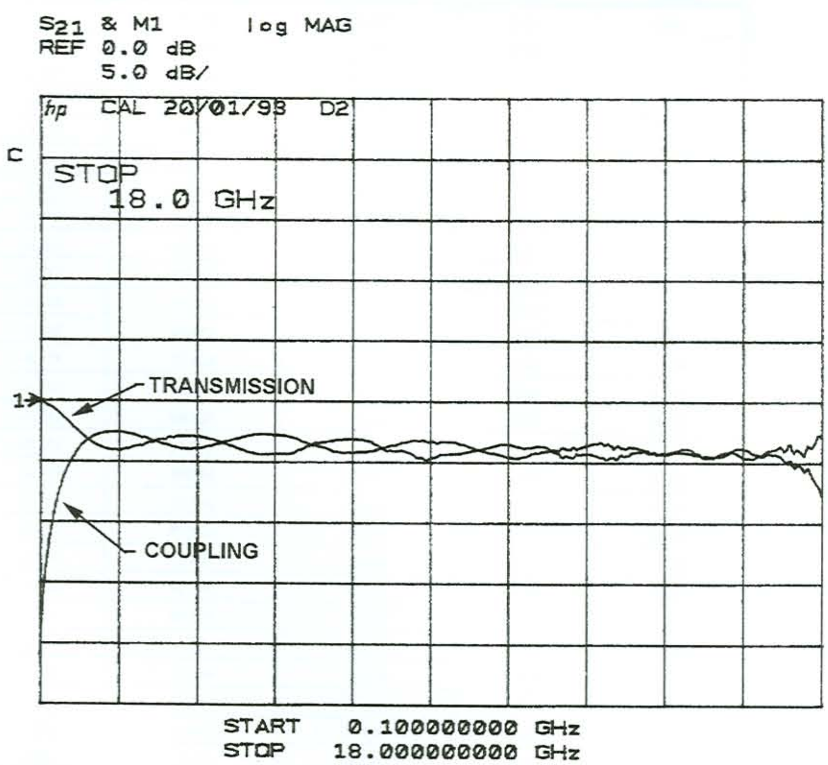


**Figure E2 : Typical 9-Section test coupler measured frequency response**

## COUPLER DESIGN RESULTS

| | | |
|---|---|---|
| Number of sections | : | 5 |
| Coupling (dB) | : | -8.343 |
| Permittivity | : | 2.200 |
| Centre frequency (Ghz) | : | 10.00 |
| System impedance (Ohm) | : | 47.17 |
| Track spacing s (mm) | : | 0.127 |
| Ground spacing b (mm) | : | 1.143 |

Normalized coupler section impedances:

Z[1] : 1.09218

Z[2] : 1.26492

Z[3] : 2.09984

| X(mm) | C(dB) | Zoe(Ohm) | Zoo(Ohm) | W(mm) | Wo(mm) |
|---|---|---|---|---|---|
| 0.000 | -3.175 | 110.948 | 20.053 | 0.589 | 0.001 |
| 0.101 | -3.181 | 110.883 | 20.081 | 0.588 | 0.018 |
| 0.202 | -3.201 | 110.598 | 20.150 | 0.589 | 0.036 |
| 0.303 | -3.233 | 110.097 | 20.258 | 0.589 | 0.055 |
| 0.405 | -3.279 | 109.387 | 20.407 | 0.591 | 0.075 |
| 0.506 | -3.339 | 108.479 | 20.595 | 0.592 | 0.095 |
| 0.607 | -3.412 | 107.383 | 20.822 | 0.595 | 0.117 |
| 0.708 | -3.499 | 106.116 | 21.088 | 0.597 | 0.139 |
| 0.809 | -3.600 | 104.693 | 21.393 | 0.601 | 0.162 |
| 0.910 | -3.717 | 103.132 | 21.735 | 0.605 | 0.186 |
| 1.011 | -3.848 | 101.452 | 22.113 | 0.610 | 0.211 |
| 1.112 | -3.995 | 99.672 | 22.527 | 0.615 | 0.237 |
| 1.214 | -4.158 | 97.812 | 22.974 | 0.621 | 0.264 |
| 1.315 | -4.337 | 95.890 | 23.454 | 0.628 | 0.292 |
| 1.416 | -4.532 | 93.926 | 23.964 | 0.636 | 0.320 |
| 1.517 | -4.744 | 91.939 | 24.503 | 0.644 | 0.349 |
| 1.618 | -4.973 | 89.944 | 25.067 | 0.653 | 0.379 |
| 1.719 | -5.218 | 87.958 | 25.654 | 0.663 | 0.409 |
| 1.820 | -5.480 | 85.996 | 26.261 | 0.673 | 0.440 |
| 1.921 | -5.757 | 84.071 | 26.885 | 0.684 | 0.470 |
| 2.023 | -6.050 | 82.194 | 27.521 | 0.695 | 0.501 |
| 2.124 | -6.357 | 80.375 | 28.167 | 0.707 | 0.532 |
| 2.225 | -6.678 | 78.625 | 28.818 | 0.719 | 0.564 |
| 2.326 | -7.010 | 76.949 | 29.470 | 0.731 | 0.594 |
| 2.427 | -7.353 | 75.353 | 30.119 | 0.744 | 0.623 |
| 2.528 | -7.705 | 73.843 | 30.760 | 0.756 | 0.651 |
| 2.629 | -8.062 | 72.422 | 31.390 | 0.769 | 0.679 |
| 2.731 | -8.424 | 71.092 | 32.003 | 0.780 | 0.707 |
| 2.832 | -8.786 | 69.855 | 32.597 | 0.792 | 0.733 |
| 2.933 | -9.147 | 68.710 | 33.168 | 0.804 | 0.757 |
| 3.034 | -9.502 | 67.658 | 33.711 | 0.814 | 0.781 |
| 3.135 | -9.849 | 66.698 | 34.225 | 0.824 | 0.802 |
| 3.236 | -10.185 | 65.827 | 34.706 | 0.834 | 0.823 |

| X(mm) | C(dB) | Zoe(Ohm) | Zoo(Ohm) | W(mm) | Wo(mm) |
|---|---|---|---|---|---|
| 3.337 | -10.506 | 65.044 | 35.153 | 0.842 | 0.842 |
| 3.438 | -10.810 | 64.345 | 35.563 | 0.850 | 0.860 |
| 3.540 | -11.093 | 63.728 | 35.938 | 0.857 | 0.876 |
| 3.641 | -11.354 | 63.188 | 36.274 | 0.863 | 0.890 |
| 3.742 | -11.590 | 62.722 | 36.574 | 0.868 | 0.903 |
| 3.843 | -11.801 | 62.324 | 36.838 | 0.873 | 0.914 |
| 3.944 | -11.985 | 61.992 | 37.066 | 0.876 | 0.923 |
| 4.045 | -12.142 | 61.718 | 37.260 | 0.879 | 0.931 |
| 4.146 | -12.274 | 61.499 | 37.424 | 0.882 | 0.938 |
| 4.247 | -12.382 | 61.329 | 37.558 | 0.884 | 0.943 |
| 4.349 | -12.466 | 61.203 | 37.666 | 0.885 | 0.947 |
| 4.450 | -12.530 | 61.115 | 37.752 | 0.886 | 0.950 |
| 4.551 | -12.576 | 61.060 | 37.817 | 0.886 | 0.952 |
| 4.652 | -12.607 | 61.031 | 37.866 | 0.886 | 0.953 |
| 4.753 | -12.625 | 61.024 | 37.901 | 0.886 | 0.954 |
| 4.854 | -12.635 | 61.032 | 37.927 | 0.886 | 0.954 |
| 4.955 | -12.639 | 61.051 | 37.946 | 0.885 | 0.954 |
| 5.056 | -12.639 | 61.074 | 37.963 | 0.885 | 0.953 |
| 5.158 | -12.640 | 61.098 | 37.979 | 0.884 | 0.953 |
| 5.259 | -12.643 | 61.118 | 37.998 | 0.884 | 0.953 |
| 5.360 | -12.650 | 61.130 | 38.021 | 0.883 | 0.953 |
| 5.461 | -12.664 | 61.131 | 38.052 | 0.883 | 0.953 |
| 5.562 | -12.687 | 61.117 | 38.091 | 0.883 | 0.954 |
| 5.663 | -12.719 | 61.086 | 38.142 | 0.883 | 0.955 |
| 5.764 | -12.763 | 61.035 | 38.205 | 0.884 | 0.957 |
| 5.866 | -12.820 | 60.964 | 38.281 | 0.884 | 0.959 |
| 5.967 | -12.891 | 60.869 | 38.371 | 0.885 | 0.963 |
| 6.068 | -12.976 | 60.752 | 38.477 | 0.886 | 0.967 |
| 6.169 | -13.077 | 60.611 | 38.598 | 0.888 | 0.971 |
| 6.270 | -13.195 | 60.446 | 38.734 | 0.889 | 0.977 |
| 6.371 | -13.329 | 60.258 | 38.887 | 0.891 | 0.983 |
| 6.472 | -13.480 | 60.047 | 39.055 | 0.893 | 0.990 |
| 6.573 | -13.649 | 59.816 | 39.238 | 0.896 | 0.998 |
| 6.675 | -13.835 | 59.566 | 39.434 | 0.898 | 1.007 |
| 6.776 | -14.038 | 59.299 | 39.644 | 0.901 | 1.017 |
| 6.877 | -14.259 | 59.017 | 39.866 | 0.904 | 1.027 |
| 6.978 | -14.496 | 58.722 | 40.099 | 0.907 | 1.038 |
| 7.079 | -14.749 | 58.417 | 40.340 | 0.910 | 1.050 |
| 7.180 | -15.017 | 58.106 | 40.590 | 0.913 | 1.062 |
| 7.281 | -15.300 | 57.789 | 40.845 | 0.916 | 1.075 |
| 7.382 | -15.596 | 57.472 | 41.104 | 0.919 | 1.088 |
| 7.484 | -15.903 | 57.155 | 41.365 | 0.922 | 1.102 |
| 7.585 | -16.221 | 56.841 | 41.627 | 0.925 | 1.116 |
| 7.686 | -16.547 | 56.534 | 41.887 | 0.928 | 1.131 |
| 7.787 | -16.879 | 56.235 | 42.144 | 0.931 | 1.145 |
| 7.888 | -17.215 | 55.947 | 42.395 | 0.933 | 1.160 |
| 7.989 | -17.551 | 55.672 | 42.639 | 0.935 | 1.175 |
| 8.090 | -17.887 | 55.411 | 42.875 | 0.937 | 1.190 |
| 8.192 | -18.217 | 55.165 | 43.100 | 0.939 | 1.204 |
| 8.293 | -18.541 | 54.937 | 43.314 | 0.941 | 1.218 |
| 8.394 | -18.853 | 54.727 | 43.516 | 0.942 | 1.231 |
| 8.495 | -19.152 | 54.535 | 43.704 | 0.943 | 1.244 |
| 8.596 | -19.434 | 54.363 | 43.877 | 0.944 | 1.256 |
| 8.697 | -19.697 | 54.210 | 44.036 | 0.945 | 1.267 |
| 8.798 | -19.938 | 54.077 | 44.181 | 0.946 | 1.277 |
| 8.899 | -20.155 | 53.963 | 44.310 | 0.946 | 1.286 |
| 9.001 | -20.348 | 53.867 | 44.424 | 0.947 | 1.294 |

| X(mm) | C(dB) | Zoe(Ohm) | Zoo(Ohm) | W(mm) | Wo(mm) |
|---|---|---|---|---|---|
| 9.102 | -20.516 | 53.789 | 44.524 | 0.947 | 1.301 |
| 9.203 | -20.658 | 53.728 | 44.611 | 0.947 | 1.307 |
| 9.304 | -20.775 | 53.682 | 44.685 | 0.947 | 1.311 |
| 9.405 | -20.868 | 53.651 | 44.747 | 0.947 | 1.315 |
| 9.506 | -20.939 | 53.632 | 44.798 | 0.946 | 1.317 |
| 9.607 | -20.991 | 53.625 | 44.840 | 0.946 | 1.319 |
| 9.708 | -21.026 | 53.627 | 44.875 | 0.945 | 1.320 |
| 9.810 | -21.048 | 53.637 | 44.903 | 0.945 | 1.321 |
| 9.911 | -21.059 | 53.652 | 44.926 | 0.944 | 1.321 |
| 10.012 | -21.063 | 53.671 | 44.946 | 0.944 | 1.321 |
| 10.113 | -21.064 | 53.692 | 44.964 | 0.943 | 1.320 |
| 10.214 | -21.065 | 53.713 | 44.982 | 0.943 | 1.320 |
| 10.315 | -21.069 | 53.732 | 45.002 | 0.942 | 1.320 |
| 10.416 | -21.080 | 53.748 | 45.025 | 0.942 | 1.320 |
| 10.518 | -21.100 | 53.758 | 45.053 | 0.941 | 1.320 |
| 10.619 | -21.133 | 53.762 | 45.086 | 0.941 | 1.321 |
| 10.720 | -21.180 | 53.758 | 45.125 | 0.940 | 1.323 |
| 10.821 | -21.245 | 53.744 | 45.173 | 0.940 | 1.325 |
| 10.922 | -21.330 | 53.720 | 45.229 | 0.940 | 1.328 |
| 11.023 | -21.436 | 53.684 | 45.295 | 0.940 | 1.332 |
| 11.124 | -21.567 | 53.638 | 45.371 | 0.939 | 1.338 |
| 11.225 | -21.723 | 53.579 | 45.457 | 0.939 | 1.344 |
| 11.327 | -21.907 | 53.507 | 45.554 | 0.939 | 1.351 |
| 11.428 | -22.120 | 53.424 | 45.661 | 0.939 | 1.360 |
| 11.529 | -22.364 | 53.328 | 45.779 | 0.940 | 1.370 |
| 11.630 | -22.641 | 53.222 | 45.908 | 0.940 | 1.382 |
| 11.731 | -22.952 | 53.104 | 46.046 | 0.940 | 1.395 |
| 11.832 | -23.299 | 52.977 | 46.194 | 0.940 | 1.409 |
| 11.933 | -23.684 | 52.840 | 46.350 | 0.940 | 1.425 |
| 12.034 | -24.108 | 52.696 | 46.514 | 0.941 | 1.443 |
| 12.136 | -24.573 | 52.545 | 46.684 | 0.941 | 1.462 |
| 12.237 | -25.082 | 52.389 | 46.860 | 0.941 | 1.483 |
| 12.338 | -25.636 | 52.229 | 47.041 | 0.941 | 1.506 |
| 12.439 | -26.238 | 52.067 | 47.225 | 0.942 | 1.532 |
| 12.540 | -26.890 | 51.904 | 47.411 | 0.942 | 1.559 |
| 12.641 | -27.595 | 51.741 | 47.598 | 0.942 | 1.588 |
| 12.742 | -28.356 | 51.581 | 47.784 | 0.942 | 1.620 |
| 12.844 | -29.178 | 51.423 | 47.968 | 0.942 | 1.654 |
| 12.945 | -30.062 | 51.271 | 48.149 | 0.942 | 1.691 |
| 13.046 | -31.015 | 51.124 | 48.326 | 0.942 | 1.731 |
| 13.147 | -32.041 | 50.984 | 48.497 | 0.941 | 1.773 |
| 13.248 | -33.146 | 50.852 | 48.661 | 0.941 | 1.819 |
| 13.349 | -34.337 | 50.728 | 48.818 | 0.941 | 1.869 |
| 13.450 | -35.622 | 50.615 | 48.966 | 0.940 | 1.923 |
| 13.551 | -37.010 | 50.511 | 49.106 | 0.940 | 1.980 |
| 13.653 | -38.513 | 50.418 | 49.235 | 0.940 | 2.043 |
| 13.754 | -40.143 | 50.335 | 49.355 | 0.939 | 2.111 |
| 13.855 | -41.917 | 50.264 | 49.464 | 0.939 | 2.185 |
| 13.956 | -43.855 | 50.203 | 49.563 | 0.938 | 2.266 |
| 14.057 | -45.981 | 50.153 | 49.652 | 0.938 | 2.354 |
| 14.158 | -48.325 | 50.113 | 49.730 | 0.937 | 2.452 |
| 14.259 | -50.928 | 50.083 | 49.799 | 0.936 | 2.561 |
| 14.360 | -53.838 | 50.062 | 49.859 | 0.936 | 2.682 |
| 14.462 | -57.121 | 50.050 | 49.911 | 0.935 | 2.820 |
| 14.563 | -60.857 | 50.045 | 49.955 | 0.935 | 2.976 |