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A FREQUENCY DOMAIN APPROACH**

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SPACE MAPPING CROSSTALK MINIMIZATION: A FREQUENCY DOMAIN APPROACH

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Abstract A frequency domain approach to minimize the crosstalk between interconnects using the aggressive Space Mapping technique is presented in this report. The aggressive Space Mapping concept is reviewed. Time domain and frequency domain strategies for crosstalk simulation are compared. A classical example of crosstalk minimization in microstrip interconnects is formulated and resolved combining the accuracy of electromagnetic simulators and the speed of circuit-theoretic models.

I. INTRODUCTION

The performance of high speed electronic systems critically depends on the quality of the transmitted signals, that should be undisturbed, undistorted, and with the desired speed. As the general speed of operation of electronic circuits increases, more and more attention must be paid to the design of interconnects.

The crosstalk minimization problem associated to the design of interconnects has gained great importance for the following reasons:

- (a) the recent advances on integrated circuits technologies (GaAs MESFET, HEMT, etc.) has reduced the single device switching time to tens of picoseconds or less,
- (b) the development of VLSI circuit technologies and packaging techniques are yielding larger chips

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within smaller devices,

- (c) the use of high density buses, at both the printed circuit board (PCB) and the multi-chip module (MCM) levels, has increased the proximity of interconnects.

When the physical length of interconnects becomes comparable to the wavelength of the highest frequency being transmitted, lumped impedance models can no longer be used for accurate simulation. Instead, a distributed transmission line model for the interconnect should be used. Further, the planar geometry used in integrated circuit technology allows that on-chip and inter-chip interconnections (PCBs, ASICs, ICs, MCMs) can be modeled as microstrip lines (Gao *et al.* [1]).

Much research has been accomplished on modeling and simulating microstrip lines as high speed interconnects. Most of the researchers have followed a time domain approach to simulate crosstalk between interconnects, measuring the transient waveform of the undesired signal. A frequency domain approach to minimize the crosstalk between interconnects using the aggressive Space Mapping technique is presented in this report. An illustration of the Space Mapping concept is presented making use of a simple example. Time domain and frequency domain strategies for crosstalk simulation are compared. A classical example of crosstalk minimization in microstrip interconnects is formulated and resolved combining the accuracy of electromagnetic simulators and the speed of empirical models.

II. COUPLED MICROSTRIP INTERCONNECTS

Fig. 1 illustrates the physical structure of two coupled microstrip interconnects, consisting of two horizontal flat conductors near a ground plane. Both conductors have the same length l and width w , and are mounted on a printed circuit wiring board with dielectric constant ϵ_r and thickness h . The conductors are separated a distance d . When an electromagnetic model is used to simulate the behavior of the interconnects, it is necessary to consider also the width of the substrate w_{PWB} as well as the height of the air box above the flat conductors h_{airbox} .

These coupled microstrip interconnects can be modeled in a variety of manners, as outlined by Bandler and Rayas-Sánchez [2]. The symbol shown in Fig. 2 will be used to represent the later coupled

microstrip interconnects as a circuit component.

III. ILLUSTRATION OF THE SPACE MAPPING TECHNIQUE

A. Space Mapping concept

Space Mapping (SM) is a novel concept for circuit design and optimization, that combines the computational efficiency of coarse models with the accuracy of fine models. The coarse models are typically empirical circuit-equivalent engineering models, which are computationally very efficient but often have a limited validity range for its parameters, beyond which the simulation results become very coarse. On the other hand, the fine models may be provided by an electromagnetic simulator, or even by direct lab measurements; they are very accurate but demand considerable resources. The SM technique establishes a mathematical link between the coarse and the fine models, and direct the bulk of CPU intensive optimization to the coarse model, while preserving the accuracy and confidence offered by the fine model. The SM technique was originally developed by Bandler *et al.* [3].

Let the vectors \mathbf{x}_c and \mathbf{x}_f represent the design parameters of the coarse and fine models, respectively, and $\mathbf{R}_c(\mathbf{x}_c)$ and $\mathbf{R}_f(\mathbf{x}_f)$ the corresponding model responses. \mathbf{R}_c is much faster to calculate but less accurate than \mathbf{R}_f .

SM optimization consists in the generation of an appropriate mapping, \mathbf{P} , from the fine model parameter space \mathbf{x}_f to the coarse model parameter space \mathbf{x}_c

$$\mathbf{x}_c = \mathbf{P}(\mathbf{x}_f) \tag{1}$$

such that

$$\mathbf{R}_c(\mathbf{P}(\mathbf{x}_f)) \approx \mathbf{R}_f(\mathbf{x}_f) \tag{2}$$

The mapping is established iteratively. In the original work [3], the initial mapping is established by performing upfront fine model analysis at a number of base points. The aggressive SM strategy minimizes the upfront effort by targeting every fine simulation at optimizing the design and progressively

refining the mapping [4].

The aggressive SM concept can be illustrated by the use of the diagram in Fig. 3. We initially perform conventional optimization using the coarse model to obtain the optimal coarse solution \mathbf{x}_c^* . Assuming that \mathbf{x}_f and \mathbf{x}_c have the same dimension, we choose the coarse optimal solution as a starting point for the fine model

$$\mathbf{x}_f = \mathbf{x}_c^* \quad (3)$$

and calculate the corresponding fine response $\mathbf{R}_f(\mathbf{x}_f)$. Then we perform parameter extraction to find the optimal value of the coarse model parameters \mathbf{x}_c , such that the coarse response sufficiently match the fine response calculated,

$$\mathbf{R}_c(\mathbf{x}_c) \approx \mathbf{R}_f(\mathbf{x}_f) \quad (4)$$

If the extracted parameters \mathbf{x}_c are approximately the same as the optimal coarse solution \mathbf{x}_c^* , then we have the space mapped solution $\bar{\mathbf{x}}_f$ and the optimization ends, otherwise, a new value of \mathbf{x}_f is generated using Broyden's formula, and the optimization continues by calculating the corresponding new fine response (see Fig. 3).

B. Space Mapping example

To exemplify the aggressive SM technique with a simple case, let us consider the problem of designing the resonant filter shown in Fig. 4b, which will be considered as the fine model. The corresponding coarse model is shown in Fig. 4a. Notice that the fine model has slightly different parameter values and includes some parasitic effects not taken into account in the coarse model. The design goal is to find C_{F1} and C_{F2} such that the voltage gain of the filter is greater than 10 from 2495MHz to 2505MHz, and less than 0.5 from 1GHz to 2GHz as well as from 3GHz to 4GHz.

A set of 20 randomly selected starting points was used to calculate the response using the coarse model before optimization (see Fig. 5). The optimal coarse response after conventional minimax

optimization for the 20 starting points is illustrated in Fig. 6. The coarse optimal solution \mathbf{x}_c^* found was $C_{C1} = 1.79436\text{pF}$ and $C_{C2} = 16.6179\text{pF}$.

The *OSA90/hope*TM [5] input file shown in Appendix A was designed to implement the aggressive SM optimization in an automated fashion, using *Datapipe*TM [6] with a macro file for data communication. The coarse and fine responses before SM optimization evaluated at the optimal coarse solution are plotted in Fig. 7. It can be seen that the fine model response at the optimal coarse solution violates the specifications. The results after the SM optimization are shown in Fig. 8. The SM solution $\bar{\mathbf{x}}_f$ found was $C_{F1} = 2.28099\text{pF}$ and $C_{F2} = 20\text{pF}$. It was obtained after only 5 evaluations of the fine model (5 SM iterations).

Finally, to compare the SM solution $\bar{\mathbf{x}}_f$ with the optimal fine solution \mathbf{x}_f^* , a conventional minimax direct optimization using the fine model was realized, obtaining the solution $C_{F1} = 2.30376\text{pF}$ and $C_{F2} = 20\text{pF}$ after 32 fine model evaluations (32 minimax iterations). The corresponding fine responses for both SM optimal solution $\bar{\mathbf{x}}_f$ and direct optimal solution \mathbf{x}_f^* are compared in Fig. 9.

IV. SIMULATION OF CROSSTALK IN INTERCONNECTS

A typical problem of crosstalk minimization involves several coupled interconnect structures as well as lumped components, that may be passive or active. The simulator must be able to calculate the voltage at any output due to a given time domain input, or the crosstalk between any pair of outputs at a particular frequency or range of frequencies.

An ordinary time domain approach to simulate a crosstalk problem is shown in diagram of Fig. 10. In this approach it is assumed that each two coupled microstrip interconnects can be represented by the corresponding coupled lossless transmission line equations and modeled by the LC per unit length matrices. These LC parameters can be obtained by using Walker's formulas [7], or by using an electromagnetic simulator such as *em*TM [8] or *IE3D*TM [9]. The SM technique can be seen as the controller that decides when to calculate the LC parameters from Walker's formulas or from the EM

simulator. Once the LC parameters are available, they can be incorporated into the AWE simulator *COFFEE2* [10] developed at Carleton University along with the lumped components and the input signal pulse, or they can be used to build up a SPICE model of the interconnect (*i.e.*, Tripathi's model [11]), and then use any circuit-level-time-domain SPICE compatible simulator, such as *Design Center*TM of Microsim [12], including the lumped components and the input signal pulse.

When the LC parameters are extracted from an EM simulator, they are valid only when the physical length l of the interconnects is much smaller than the wavelength of the highest frequency of interest. Therefore, if the input pulse signal $V_{s(t)}$ (usually a trapezoid pulse) contains significant harmonics whose frequencies are larger than the frequency $Freq$ used by the EM simulator (see Fig. 10), the LC matrices are no longer sufficient to model the interconnects, and the accuracy of the EM simulator is no longer retained.

The simulation flow in a frequency domain approach is illustrated in Fig. 11. Here the S parameters of each two coupled microstrips can be calculated by using the empirical Kirschning and Jansen model [13], or by using an EM simulator. These S parameters can be connected by circuit theory to the lumped components within *OSA90/hope*TM, and the crosstalk can be computed with a conventional AC analysis incorporating a postprocessing suitable formula to calculate voltage gains (crosstalk between any two nodes) in terms of S parameters, as proposed by Bandler and Rayas-Sánchez [2].

In the frequency domain approach the S parameters of the microstrip interconnects obtained from the EM simulator are calculated at the same frequency $Freq$ used by *OSA90/hope*TM to analyze the complete circuit (see Fig. 11), and therefore the accuracy of the EM simulator is preserved.

VI. SPACE MAPPING CROSSTALK MINIMIZATION

A. Coarse and fine models comparison

The Kirschning and Jansen model using the built-in linear elements MSCL (two-conductor symmetrical coupled microstrip lines) and MSUB (microstrip substrate definition) directly available in *OSA90/hope*TM was compared to the corresponding electromagnetic model using *em*TM. These two

models will be used as coarse and fine models, respectively, in the next section for SM crosstalk minimization.

The following parameters were used for both models: $w = 0.5$ mm, $h = 2$ mm, $\epsilon_r = 9.75$ (alumina), $\mu_r = 1$, $d = 2$ mm and $l = 10$ mm. Additionally, for Sonnet's model were used $h_{airbox} = 5$ mm, $w_{PWB} = 10$ mm and an area resolution of 20 cells (x -direction) by 80 cells (y -direction). The corresponding S parameters are compared in Fig. 12, for a frequency range from 200MHz to 20GHz. It can be seen that the Kirschning-Jansen's model is a good approximation of the Sonnet's model only for low frequencies.

B. Problem formulation

A classical problem of crosstalk minimization that has been studied from different points of view [14, 15, 16, 17] is illustrated in Fig. 13. For the circuit shown in Fig. 13, assuming that

- (a) the material of the substrate (ϵ_r and loss tangent) is fixed and the same for the three coupled microstrip interconnects
- (b) w and h are the same for the three coupled microstrips
- (c) d and l can be different for each two coupled microstrips
- (d) the interconnects parameters w , h , d and l are optimization variables
- (e) the capacitor C_1 as well as the resistances R_1 , R_2 , R_4 , R_5 , R_6 and R_8 are also optimization variables
- (f) all the remaining lumped components values are fixed

design the circuit so that the crosstalk from V_a to V_b is less than -33 dB within an operating frequency range from 8 GHz to 14 GHz, and the parameters shown in Table I are satisfied.

C. Results

Before optimization, the simulation results obtained for the circuit in Fig. 13 with the coarse model are shown in Fig. 14, using the starting values indicated in Table II.

Running a conventional minimax optimization process for the coarse circuit, the crosstalk specification is satisfied as shown in Fig. 15. The optimal coarse solution indicated in Table II was

found after 22 minutes and 48 seconds of CPU time, using *OSA90/hope*TM through a HP Apollo 715/33 connected in a Telnet session to a Sun Sparc station 10.

To parameterize each of the microstrip coupled lines for optimization the Geometric Capture [18] technique available in *Empipe*TM [19] was used. Using *Empipe*TM, five geometry files were created, the first one containing the geometric model at the nominal parameter values (the same as in Section VI *a*) and the remaining for each of the perturbed parameters (w , h , d and l).

Both coarse and fine responses evaluated at the optimal coarse solution are plotted in Fig. 16. It can be seen that the fine response at the optimal coarse solution violates the specification. A single frequency sweep simulation for the fine circuit took approximately 2 hours and 55 minutes, from 7 GHz to 15 GHz with an step size of 0.1 GHz, using the same platform.

The *OSA90/hope*TM input file shown in Appendix B was designed to implement the aggressive SM optimization in an automated fashion, using *Datapipe*TM with a macro file for data communication. The corresponding “include” files to obtain the S parameters from the *em*TM simulator were generated using *Empipe*TM. To avoid possible difficulties in the convergence of the SM technique due to off-grid point simulations [20], the interpolation feature of *Empipe*TM was enabled for the parameter extraction process.

In order to save even more EM simulations during the SM optimization, the coarse and fine responses were compared only at seven frequency points within the range of the specification (from 12.5 GHz to 14 GHz with an step of 0.25 GHz) in the parameter extraction phase. This frequency range was chosen taking advantage of the natural behavior of the crosstalk, that tends to increase with the frequency: if the fine response match the coarse response at that range of frequencies, then it will probably satisfy the specification for the whole frequency range.

Several matching goals were experimented during the parameter extraction phase. When the crosstalk responses expressed in dB were directly compared, the SM algorithm ended at the first iteration because the coarse parameters were mistakenly extracted and agreed with the optimal coarse solution.

The SM algorithm oscillated when the magnitude and phases of the S parameters were taken as matching functions. A better behavior of the objective function for the SM optimization was obtained when the real and imaginary parts of S_{11} and S_{21} for the coarse and fine circuits were compared, obtaining after 8 SM iterations the results shown in Fig. 17, which clearly are not satisfactory. Finally, the crosstalk responses expressed in radians were selected as matching goals. Since the convergence of the parameter extraction optimization was fast for this matching goal, the number of iterations for the Huber optimizer in the parameter extraction phase was limited to 10. To emphasize the relative importance of w , h , l_2 , d_2 and C_1 , in the crosstalk from V_a to V_b (see Fig. 13), weighting factors were introduced in the objective function to match the extracted coarse parameters to the coarse optimal solution, as detailed in Appendix B. The results after the aggressive SM optimization are shown in Fig. 18, being the SM solution for the fine parameter space the one indicated in Table II. The SM fine solution was found after 5 SM iterations that took only 7 minutes and 46 seconds of CPU time on the same platform.

VII. CONCLUSIONS

A frequency domain approach to efficiently minimize the crosstalk between interconnects using the aggressive Space Mapping technique is presented. A comparison between the Kirschning-Jansen model for two coupled microstrip lines and the corresponding electromagnetic model used by *em*TM shows important differences in their behavior for high frequencies. These models were used as the coarse and fine models, respectively, during the aggressive SM optimization. By comparing the coarse and fine responses at a few frequency points during the parameter extraction phase of the aggressive SM technique, the optimization time is reduced even more. The functions selected as matching goals for the parameter extraction critically influenced the convergence of the SM technique. The frequency domain method proposed permits a straightforward crosstalk minimization in the frequency range of interest, avoiding the calculation of intermediate parameters, as the LC matrices typically used in time domain methods.

APPENDIX A: OSA90/hope™ FILE TO ILLUSTRATE THE AGGRESSIVE SM TECHNIQUE

```

! ~~~~~
!                               Illustration of the Space Mapping Concept
! ~~~~~

Expression

!      Cc1_opt: 1.79436;    ! Optimal capacitance 1 (in pF) for the coarse model
!      Cc2_opt: 16.6179;   ! Optimal capacitance 2 (in pF) for the coarse model

!      Xc[2]=[Cc1 Cc2]   Coarse design parameters (pF, pF)
!      Xf[2]=[Cf1 Cf2]   Fine design parameters (pF, pF)

      Xc_opt[2]: [1.79436 16.6179];
      Xf[2]: [?1.5 1.79436 2.5? ?10 16.6179 20?];

      Char PE_ckt[]="
!.....
!                               Parameter extraction file
Model
      Xf[2]:*;
      Xc[2]= [?1.79436? ?16.6179?];

!      COARSE MODEL:
CAP      @c1 @c2   C=(Xc[1]*1E-12);
IND      @c2 @c3   L=2.5nH;
CAP      @c3 0     C=(Xc[2]*1E-12);
RES      @c3 0     R=50oh;

      PORTS @c1 0 @c3 0 ; ! Ports in coarse model (ports 1-2)

!      FINE MODEL:
CAP      @f1 @f2   C=(Xf[1]*1E-12);
CAP      @f1 @f2   C=0.01pF;
RES      @f1 @f2   R=10450oh;
IND      @f2 @f3   L=1.9543nH;
CAP      @f3 0     C=(Xf[2]*1E-12);
RES      @f3 0     R=50oh;

      PORTS @f1 0 @f3 0 ; ! Ports in fine model (ports 3-4)

CIRCUIT;

!      Calculus of the crosstalk voltage gain:

      MNum_Av= 2*MS21;
      PNum_Av= PS21;
      RI2MP((1+rS11),iS11, MS11M1,PS11M1);
      RI2MP((1-rS22),iS22, M1MS22,P1MS22);
      MP2RI((MS11M1*M1MS22),(PS11M1+P1MS22), rDen1, iDen1);
      MP2RI((MS12*MS21),(PS12+PS21), rDen2,iDen2);
      RI2MP((rDen1+rDen2),(iDen1+iDen2),MDen_Av,PDen_Av);
      "Av (coarse)"= MNum_Av/MDen_Av;
      "Av dB (coarse)"= (20*log10("Av (coarse)"));

      MNum_Avf= 2*MS43;
      PNum_Avf= PS43;
      RI2MP((1+rS33),iS33, MS33M1,PS33M1);
      RI2MP((1-rS44),iS44, M1MS44,P1MS44);
      MP2RI((MS33M1*M1MS44),(PS33M1+P1MS44), rDen1f, iDen1f);
      MP2RI((MS34*MS43),(PS34+PS43), rDen2f,iDen2f);
      RI2MP((rDen1f+rDen2f),(iDen1f+iDen2f),MDen_Avf,PDen_Avf);
      "Av (fine)"= MNum_Avf/MDen_Avf;
      "Av dB (fine)"= (20*log10("Av (fine)"));

end

Sweep
      Xc;
      AC:
          FREQ:  from 1000MHz to 2400MHz step=20MHz
                  from 2400MHz to 2600MHz step=10MHz
                  from 2600MHz to 4000MHz step=20MHz

```

```

        "Av (coarse)" "Av (fine)"
        {XSWEEP Y="Av (coarse)".white.cross&"Av (fine)".white
        X_TITLE="Frequency (Hz)"
        Y_TITLE="Av (coarse), Av (fine)"
        SPEC= (from 1000MHz to 2000MHz, < 0.5).white&
              (from 2495MHz to 2505MHz, > 10).white&
              (from 3000MHz to 4000MHz, < 0.5).white
        TITLE: "Magnitude of the Voltage Gain"};
end

Specification
AC:
    FREQ: from 1000MHz to 2000MHz step=20MHz
        "Av (fine)" = "Av (coarse)";
AC:
    FREQ: from 2490Hz to 2510MHz step 4MHz
        "Av (fine)" = "Av (coarse)";
AC:
    FREQ: from 3000MHz to 4000MHz step=20MHz
        "Av (fine)" = "Av (coarse)";
end

Control
Non_microwave_units;
Optimizer=Huber;
N_iterations=30;
Display_N_digits=6;
Accuracy=1.0e-5;
Huber_threshold=0.15;
end
!
!           End of parameter extraction file
!.....
!           ";

!           Macro command for child OSA90:

Char PE_macro[]="message,'OSA90 Child for Parameter
Extraction',wait3,exit,'dx',up,up,right,down,enter,enter,message,'before parameter
extraction...',wait3,esc,'o',enter,'dx',up,up,right,down,enter,enter,message,'after parameter
extraction...',wait3,esc,esc";

Datapipe: COM File="osa90 -pio"
             N_INPUT=5      INPUT=(4,PE_ckt,PE_macro,Xf)
             N_OUTPUT=2     OUTPUT=(Xc[2]);

end

Specification
Xc[1] = Xc_opt[1] W=3;
Xc[2] = Xc_opt[2] W=0.1;
end

Trace
end

Mapping
end

Control
Non_microwave_units;
Optimizer=Space_Mapping;
N_iterations=15;
Accuracy=1.0e-5;
end

Model
! COARSE MODEL:
CAP @c1 @c2 C=(Xc_opt[1]*1E-12);
IND @c2 @c3 L=2.5nH;
CAP @c3 0 C=(Xc_opt[2]*1E-12);
RES @c3 0 R=50oh;

PORTS @c1 0 @c3 0 ; ! Ports in coarse model (ports 1-2)

! FINE MODEL:
CAP @f1 @f2 C=(Xf[1]*1E-12);

```

```

CAP      @f1 @f2  C=0.01pF;
RES      @f1 @f2  R=10450oh;
IND      @f2 @f3  L=1.9543nH;
CAP      @f3 0    C=(Xf[2]*1E-12);
RES      @f3 0    R=50oh;

PORTS @f1 0 @f3 0 ; ! Ports in fine model (ports 3-4)

CIRCUIT;

!      Calculus of the crosstalk voltage gain:

MNum_Av= 2*MS21;
PNum_Av= PS21;
RI2MP((1+rS11),iS11, MS11M1,PS11M1);
RI2MP((1-rS22),iS22, M1MS22,P1MS22);
MP2RI((MS11M1*M1MS22),(PS11M1+P1MS22), rDen1, iDen1);
MP2RI((MS12*MS21),(PS12+PS21), rDen2,iDen2);
RI2MP((rDen1+rDen2),(iDen1+iDen2),MDen_Av,PDen_Av);
"Av (coarse)"= MNum_Av/MDen_Av;
"Av dB (coarse)"= (20*log10("Av (coarse)"));

MNum_Avf= 2*MS43;
PNum_Avf= PS43;
RI2MP((1+rS33),iS33, MS33M1,PS33M1);
RI2MP((1-rS44),iS44, M1MS44,P1MS44);
MP2RI((MS33M1*M1MS44),(PS33M1+P1MS44), rDen1f, iDen1f);
MP2RI((MS34*MS43),(PS34+PS43), rDen2f,iDen2f);
RI2MP((rDen1f+rDen2f),(iDen1f+iDen2f),MDen_Avf,PDen_Avf);
"Av (fine)"= MNum_Avf/MDen_Avf;
"Av dB (fine)"= (20*log10("Av (fine)"));

end

Sweep
AC:
  FREQ:  from 1000MHz to 2400MHz step=20MHz
         from 2400MHz to 2600MHz step=10MHz
         from 2600MHz to 4000MHz step=20MHz
         "Av (coarse)" "Av (fine)"
         {XSWEEP Y="Av (coarse)".white.cross&"Av (fine)".white
          X_TITLE="Frequency (Hz)"
          Y_TITLE="Av (coarse), Av (fine)"
          SPEC= (from 1000MHz to 2000MHz, < 0.5).white&
                (from 2495MHz to 2505MHz, > 10).white&
                (from 3000MHz to 4000MHz, < 0.5).white
          TITLE: "Magnitude of the Voltage Gain"};

Xc;

end

```

APPENDIX B: OSA90/hope™ FILE FOR SM CROSSTALK MINIMIZATION

```

!
!           ~~~~~
!           Crosstalk minimization in interconnects
!           using the aggressive SM technique
!           ~~~~~
!
Expression

Fmin:  8GHz;           ! Low frequency limit for the crosstalk specification
Fmax:  14GHz;          ! High frequency limit for the crosstalk specification
MXTdB: -33;           ! Maximum crosstalk in dB (specification)
MXT: (10^(MXTdB/20)); ! Maximum crosstalk (specification)

eps_r : 9.75;          ! Dielectric constant of the PWB laminate
w_oc  : 0.251122;      ! Optimal coarse width of each flat conductor in the PCB (mm)
h_oc  : 0.5;           ! Optimal coarse thickness of the PWB laminate (mm)

L1_oc: 43.0281;        ! Optimal coarse length of the flat conductors for each
L2_oc: 28.4045;        ! interconnect (mm)
L3_oc: 10.0136;

D1_oc: 2.5043; ! Optimal coarse distance between the conductors for each interconnect (mm)
D2_oc: 3;
D3_oc: 1.04094;

R1_oc: 50.0111;        ! Lumped components values for the optimal coarse response
R2_oc: 74.9997;
R4_oc: 84.1879;
R5_oc: 25.057;
R6_oc: 50.2838;
R8_oc: 100;
C1_oc: 4.50848;

R3: 100oh;           ! Fixed lumped components
R7: 100oh;
R9: 50oh;
R10: 100oh;
LL: 10nH;
C2: 2pF;
C3: 1pF;

Xoc[15] = [w_oc h_oc L1_oc L2_oc L3_oc D1_oc D2_oc D3_oc R1_oc R2_oc R4_oc R5_oc R6_oc
R8_oc C1_oc];
Xf[15]=[?0.25 0.251122 ? ? ?0.5 0.5 3? ?40 43.0281 50? ?20 28.4045 30? ?8 10.0136 12? ?0.5
2.5043 5? ?0.5 3 3? ?0.5 1.04094 2? ?25oh 50.0111oh 150oh? ?25oh 74.9997oh 150oh? ?0.01oh
84.1879oh 150oh? ?0.01oh 25.057oh 150oh? ?25oh 50.2838oh 150oh? ?25oh 100oh 150oh? ?0.01
4.50848 10?];

Char PE_ckt[]="
!.....
!.....
!
!           Parameter extraction file
Model
Xf[15]:*;
#include "mcs_cl_paex.inc";
xc[15]=[?0.251122? ?0.5? ?43.0281? ?28.4045? ?10.0136? ?2.5043? ?3? ?1.04094? ?50.0111oh?
?74.9997oh? ?84.1879oh? ?25.057oh? ?50.2838oh? ?100oh? ?4.50848?];

Fmin:  8GHz;           ! Low frequency limit for the crosstalk specification
Fmax:  14GHz;          ! High frequency limit for the crosstalk specification
MXTdB: -33;           ! Maximum crosstalk in dB (specification)
MXT: (10^(MXTdB/20)); ! Maximum crosstalk (specification)

eps_r : 9.75;          ! Dielectric constant of the PWB laminate
R3: 100oh;           ! Fixed lumped components
R7: 100oh;
R9: 50oh;
R10: 100oh;
LL: 10nH;
C2: 2pF;

```

```

C3: 1pF;

! COARSE MODEL:
RES 0 @c1 R=Xc[9]; ! R1
RES @c2 0 R=Xc[10]; ! R2
RES @c4 0 R=R3;
RES @c3 @c5 R=Xc[11]; ! R4
RES @c3 @c7 R=Xc[12]; ! R5
RES @c6 0 R=Xc[13]; ! R6
RES @cb 0 R=R7;
RES @c8 0 R=Xc[14]; ! R8
RES @c9 @c10 R=R9;
RES @cd 0 R=R10;
IND @c10 @cc L=LL;
CAP @c3 0 C=(Xc[15]*1pF); ! C1
CAP @ca 0 C=C2;
CAP @cc 0 C=C3;

MSUB EPSR=eps_r H=(Xc[2]*1mm);
MSCL @c1 @c2 @c4 @c3 W=(Xc[1]*1mm) L=(Xc[3]*1mm) S=(Xc[6]*1mm);
MSCL @c5 @c6 @cb @ca W=(Xc[1]*1mm) L=(Xc[4]*1mm) S=(Xc[7]*1mm);
MSCL @c7 @c8 @cd @c9 W=(Xc[1]*1mm) L=(Xc[5]*1mm) S=(Xc[8]*1mm);

PORT @ca 0; ! Input port (Va_coarse) Port1
PORT @cb 0; ! Output Port (Vb_coarse) Port2

! FINE MODEL:
RES 0 @f1 R=Xf[9]; ! R1
RES @f2 0 R=Xf[10]; ! R2
RES @f4 0 R=R3;
RES @f3 @f5 R=Xf[11]; ! R4
RES @f3 @f7 R=Xf[12]; ! R5
RES @f6 0 R=Xf[13]; ! R6
RES @fb 0 R=R7;
RES @f8 0 R=Xf[14]; ! R8
RES @f9 @f10 R=R9;
RES @fd 0 R=R10;
IND @f10 @fc L=LL;
CAP @f3 0 C=(Xf[15]*1pF); ! C1
CAP @fa 0 C=C2;
CAP @fc 0 C=C3;

MCS_CL_PAEX @f1 @f2 @f3 @f4 0
l=(Xf[3]*1mm) d=(Xf[6]*1mm)
w=(Xf[1]*1mm) h=(Xf[2]*1mm);

MCS_CL_PAEX @f5 @f6 @fa @fb 0
l=(Xf[4]*1mm) d=(Xf[7]*1mm)
w=(Xf[1]*1mm) h=(Xf[2]*1mm);

MCS_CL_PAEX @f7 @f8 @f9 @fd 0
l=(Xf[5]*1mm) d=(Xf[8]*1mm)
w=(Xf[1]*1mm) h=(Xf[2]*1mm);

PORT @fa 0; ! Input port (Va_fine) Port 3
PORT @fb 0; ! Output Port (Vb_fine) Port 4

CIRCUIT;

! Calculus of the crosstalk voltage gain:

MNum_Av= 2*MS21;
PNum_Av= PS21;
RI2MP((1+rS11),iS11, MS11M1,PS11M1);
RI2MP((1-rS22),iS22, M1MS22,P1MS22);
MP2RI((MS11M1*M1MS22),(PS11M1+P1MS22), rDen1, iDen1);
MP2RI((MS12*MS21),(PS12+PS21), rDen2,iDen2);
RI2MP((rDen1+rDen2),(iDen1+iDen2),MDen_Av,PDen_Av);
"Xtk coarse"= MNum_Av/MDen_Av;
"Xtk_dB (coarse)"= (20*log10("Xtk coarse"));

MNum_Avf= 2*MS43;
PNum_Avf= PS43;
RI2MP((1+rS33),iS33, MS33M1,PS33M1);
RI2MP((1-rS44),iS44, M1MS44,P1MS44);
MP2RI((MS33M1*M1MS44),(PS33M1+P1MS44), rDen1f, iDen1f);

```

```

MP2RI((MS34*MS43),(PS34+PS43), rDen2f,iDen2f);
RI2MP((rDen1f+rDen2f),(iDen1f+iDen2f),MDen_Avf,PDen_Avf);
"Xtk_fine" = MNum_Avf/MDen_Avf;
"Xtk_dB (fine)" = (20*log10("Xtk_fine"));

end

Sweep
  Xc;
  AC:
    FREQ: from 12.5GHz to 14GHz step=0.25GHz
    "Xtk_dB (coarse)" "Xtk_dB (fine)"
    {XSWEEEP Y="Xtk_dB (coarse)".white.cross & "Xtk_dB (fine)".white
      Y_TITLE="Crosstalk in dB (coarse & fine responses)"
      X_TITLE="Frequency (GHz)"
      SPEC=(from Fmin to Fmax, < (MXTdB) ).white
      TITLE: "Crosstalk from voltage Va to voltage Vb"}
end

Specification
  AC:
    FREQ: from 12.5GHz to 14GHz step=0.25GHz
    "Xtk_coarse"="Xtk_fine"
end

Control
  Optimizer=Huber;
  N_iterations=10;
  Display_N_digits=6;
  Accuracy=1.0e-6;
  Huber_threshold=0.15;
end
!.....
!
  ";

!
  Macro command for child OSA90:

  Char PE_macro[]="message,'OSA90 Child for Parameter
Extraction',wait3,exit,'dx',up,up,right,down,enter,enter,enter,enter,enter,enter,enter,enter,enter,enter,enter,enter,enter,message,'after
parameter extraction...',wait3,esc,'o',enter,'dx',up,up,right,down,enter,enter,enter,enter,enter,enter,enter,enter,enter,message,'after
parameter extraction...',wait3,esc,esc";

  Datapipe: COM File="osa90 -pio"
                N_INPUT=18 INPUT=(4,PE_ckt,PE_macro,Xf)
                N_OUTPUT=15 OUTPUT=(Xc[15]);
end

Specification
! Xc = Xoc
! Xc[15] = [w h L1 L2 L3 D1 D2 D3 R1 R2 R4 R5 R6 R8 C1];

Xc[1] = Xoc[1] W=0.01
Xc[2] = Xoc[2] W=0.01
Xc[3] = Xoc[3] W=0.001
Xc[4] = Xoc[4] W=1.0
Xc[5] = Xoc[5] W=0.001
Xc[6] = Xoc[6] W=0.001
Xc[7] = Xoc[7] W=1.0
Xc[8] = Xoc[8] W=0.001
Xc[9] = Xoc[9] W=0.001
Xc[10] = Xoc[10] W=0.001
Xc[11] = Xoc[11] W=0.01
Xc[12] = Xoc[12] W=0.001
Xc[13] = Xoc[13] W=0.01
Xc[14] = Xoc[14] W=0.001
Xc[15] = Xoc[15] W=10;

end

Trace
end

Mapping
end

```



```

Control
    Optimizer=Space_Mapping;
    N_iterations=15;
    Accuracy=1.0e-5;
end

Model

    #include "mcs_cl_dspy.inc";

!
    COARSE MODEL:
    RES    0      @c1      R=Xoc[9]; ! R1
    RES    @c2    0        R=Xoc[10]; ! R2
    RES    @c4    0        R=R3;
    RES    @c3    @c5      R=Xoc[11]; ! R4
    RES    @c3    @c7      R=Xoc[12]; ! R5
    RES    @c6    0        R=Xoc[13]; ! R6
    RES    @cb    0        R=R7;
    RES    @c8    0        R=Xoc[14]; ! R8
    RES    @c9    @c10     R=R9;
    RES    @cd    0        R=R10;
    IND    @c10   @cc      L=LL;
    CAP    @c3    0        C=(Xoc[15]*1pF); ! C1
    CAP    @ca    0        C=C2;
    CAP    @cc    0        C=C3;

    MSUB    EPSR=eps_r H=(Xoc[2]*1mm);
    MSCL    @c1 @c2 @c4 @c3 W=(Xoc[1]*1mm) L=(Xoc[3]*1mm) S=(Xoc[6]*1mm);
    MSCL    @c5 @c6 @cb @ca W=(Xoc[1]*1mm) L=(Xoc[4]*1mm) S=(Xoc[7]*1mm);
    MSCL    @c7 @c8 @cd @c9 W=(Xoc[1]*1mm) L=(Xoc[5]*1mm) S=(Xoc[8]*1mm);

    PORT    @ca    0;      ! Input port (Va_coarse) Port1
    PORT    @cb    0;      ! Output Port (Vb_coarse) Port2

!
    FINE MODEL:
    RES    0      @f1      R=Xf[9]; ! R1
    RES    @f2    0        R=Xf[10]; ! R2
    RES    @f4    0        R=R3;
    RES    @f3    @f5      R=Xf[11]; ! R4
    RES    @f3    @f7      R=Xf[12]; ! R5
    RES    @f6    0        R=Xf[13]; ! R6
    RES    @fb    0        R=R7;
    RES    @f8    0        R=Xf[14]; ! R8
    RES    @f9    @f10     R=R9;
    RES    @fd    0        R=R10;
    IND    @f10   @fc      L=LL;
    CAP    @f3    0        C=(Xf[15]*1pF); ! C1
    CAP    @fa    0        C=C2;
    CAP    @fc    0        C=C3;

    MCS_CL_DSPY @f1 @f2 @f3 @f4 0
    MODEL=0
    l=(Xf[3]*1mm) d=(Xf[6]*1mm)
    w=(Xf[1]*1mm) h=(Xf[2]*1mm);

    MCS_CL_DSPY @f5 @f6 @fa @fb 0
    MODEL=0
    l=(Xf[4]*1mm) d=(Xf[7]*1mm)
    w=(Xf[1]*1mm) h=(Xf[2]*1mm);

    MCS_CL_DSPY @f7 @f8 @f9 @fd 0
    MODEL=0
    l=(Xf[5]*1mm) d=(Xf[8]*1mm)
    w=(Xf[1]*1mm) h=(Xf[2]*1mm);

    PORT    @fa    0;      ! Input port (Va_fine) Port 3
    PORT    @fb    0;      ! Output Port (Vb_fine) Port 4

    CIRCUIT;

!
    Calculus of the crosstalk voltage gain:

    MNum_Av= 2*MS21;
    PNum_Av= PS21;
    RI2MP((1+rS11),iS11, MS11M1,PS11M1);

```

```

RI2MP((1-rS22),iS22, M1MS22,P1MS22);
MP2RI((MS11M1*M1MS22),(PS11M1+P1MS22), rDen1, iDen1);
MP2RI((MS12*MS21),(PS12+PS21), rDen2,iDen2);
RI2MP((rDen1+rDen2),(iDen1+iDen2),MDen_Av,PDen_Av);
"Xtk coarse"= MNum_Av/MDen_Av;
"Xtk_dB (coarse)"= (20*log10("Xtk coarse"));

MNum_Avf= 2*MS43;
PNum_Avf= PS43;
RI2MP((1+rS33),iS33, MS33M1,PS33M1);
RI2MP((1-rS44),iS44, M1MS44,P1MS44);
MP2RI((MS33M1*M1MS44),(PS33M1+P1MS44), rDen1f, iDen1f);
MP2RI((MS34*MS43),(PS34+PS43), rDen2f,iDen2f);
RI2MP((rDen1f+rDen2f),(iDen1f+iDen2f),MDen_Avf,PDen_Avf);
"Xtk fine"= MNum_Avf/MDen_Avf;
"Xtk_dB (fine)"= (20*log10("Xtk fine"));

end

Sweep
AC:
FREQ: from 7GHz to 15GHz step=0.1GHz
"Xtk_dB (coarse)" "Xtk_dB (fine)"
{XSWEEP Y="Xtk_dB (coarse)".white.cross & "Xtk_dB (fine)".white
Y_TITLE="Crosstalk in dB (coarse & fine responses)"
X_TITLE="Frequency (GHz)"
SPEC=(from Fmin to Fmax, < (MXTdB) ).white
TITLE: "Crosstalk from voltage Va to voltage Vb"}

end

```

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TABLE I
PARAMETERS FOR CIRCUIT IN FIG. 14

| Fixed parameters | Optimization parameters |
|-----------------------------|---|
| $\epsilon_r = 9.75$ | $0.25 \text{ mm} \leq w \leq 2 \text{ mm}$ |
| $\mu_r = 1$ | $0.5 \text{ mm} \leq h \leq 3 \text{ mm}$ |
| $w_{PWB} = 10 \text{ mm}$ | $0.5 \text{ mm} \leq d_1 \leq 5 \text{ mm}$ |
| $h_{airbox} = 5 \text{ mm}$ | $0.5 \text{ mm} \leq d_2 \leq 3 \text{ mm}$ |
| $R_3 = 100 \Omega$ | $0.5 \text{ mm} \leq d_3 \leq 2 \text{ mm}$ |
| $R_7 = 100 \Omega$ | $40 \text{ mm} \leq l_1 \leq 50 \text{ mm}$ |
| $R_9 = 50 \Omega$ | $20 \text{ mm} \leq l_2 \leq 30 \text{ mm}$ |
| $R_{10} = 100 \Omega$ | $8 \text{ mm} \leq l_3 \leq 12 \text{ mm}$ |
| $L_L = 10 \text{ nH}$ | $25 \Omega \leq R_1 \leq 150 \Omega$ |
| $C_2 = 2 \text{ pF}$ | $25 \Omega \leq R_2 \leq 150 \Omega$ |
| $C_3 = 1 \text{ pF}$ | $0 \Omega \leq R_4 \leq 150 \Omega$ |
| | $0 \Omega \leq R_5 \leq 150 \Omega$ |
| | $25 \Omega \leq R_6 \leq 150 \Omega$ |
| | $25 \Omega \leq R_8 \leq 150 \Omega$ |
| | $0.01 \text{ pF} \leq C_1 \leq 10 \text{ pF}$ |

TABLE II
PARAMETERS VALUES DURING OPTIMIZATION

| Parameter | Starting value | Optimal coarse | SM fine solution |
|--------------------|----------------|----------------|------------------|
| w (mm) | 0.58 | 0.251122 | 0.250184 |
| h (mm) | 1.17 | 0.5 | 0.5 |
| d_1 (mm) | 2.49 | 2.5043 | 2.5043 |
| d_2 (mm) | 1.2 | 3 | 3 |
| d_3 (mm) | 1.1 | 1.04094 | 1.04094 |
| l_1 (mm) | 43 | 43.0281 | 43.0295 |
| l_2 (mm) | 28 | 28.4045 | 29.8001 |
| l_3 (mm) | 10 | 10.0136 | 10.0137 |
| R_1 (Ω) | 50 | 50.0111 | 50.0109 |
| R_2 (Ω) | 75 | 74.9997 | 74.9997 |
| R_4 (Ω) | 25 | 84.1879 | 83.9004 |
| R_5 (Ω) | 25 | 25.057 | 25.057 |
| R_6 (Ω) | 50 | 50.2838 | 50.235 |
| R_8 (Ω) | 100 | 100 | 100 |
| C_1 (pF) | 1 | 4.50848 | 7.82345 |

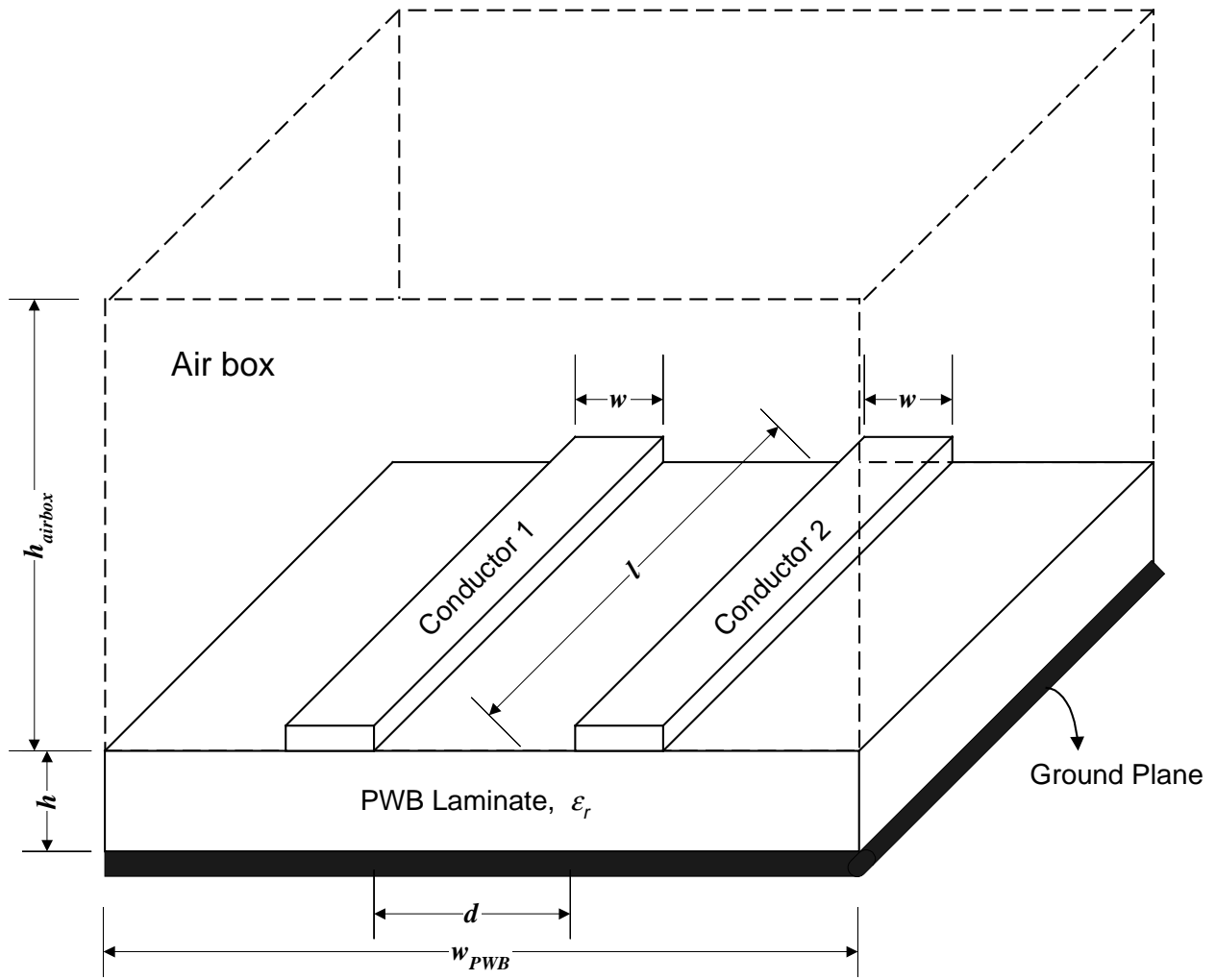


Fig. 1 Physical structure of two coupled microstrip interconnects.

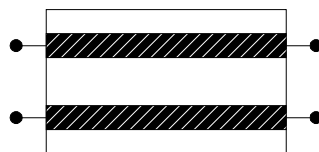


Fig. 2 Electrical symbol of two coupled microstrip interconnects.

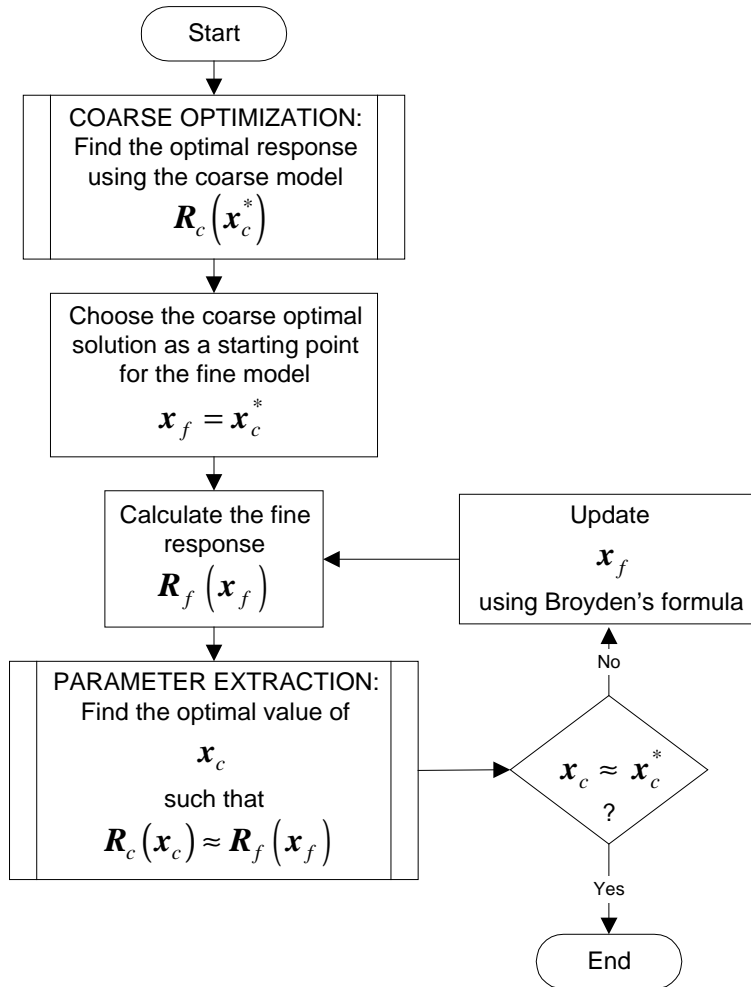


Fig. 3 Space Mapping concept.

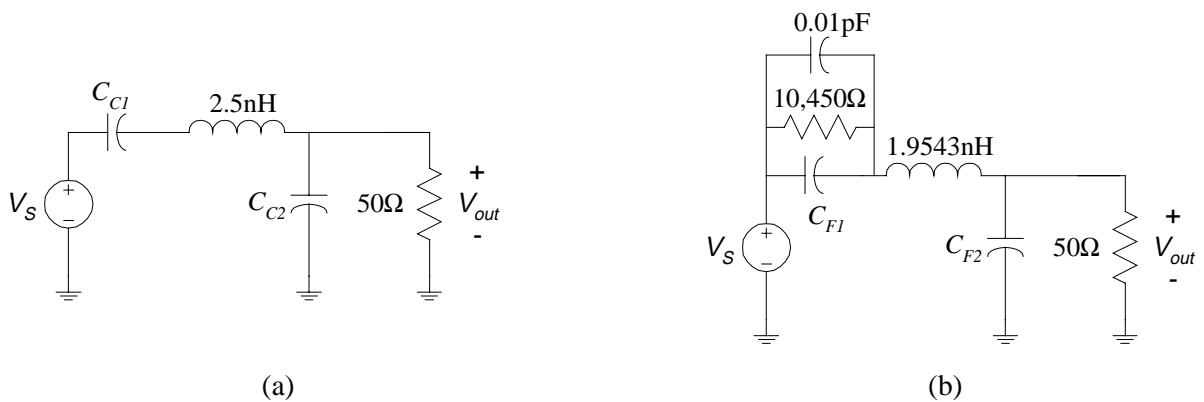


Fig. 4 Models used to illustrate the SM technique: (a) coarse; (b) fine.

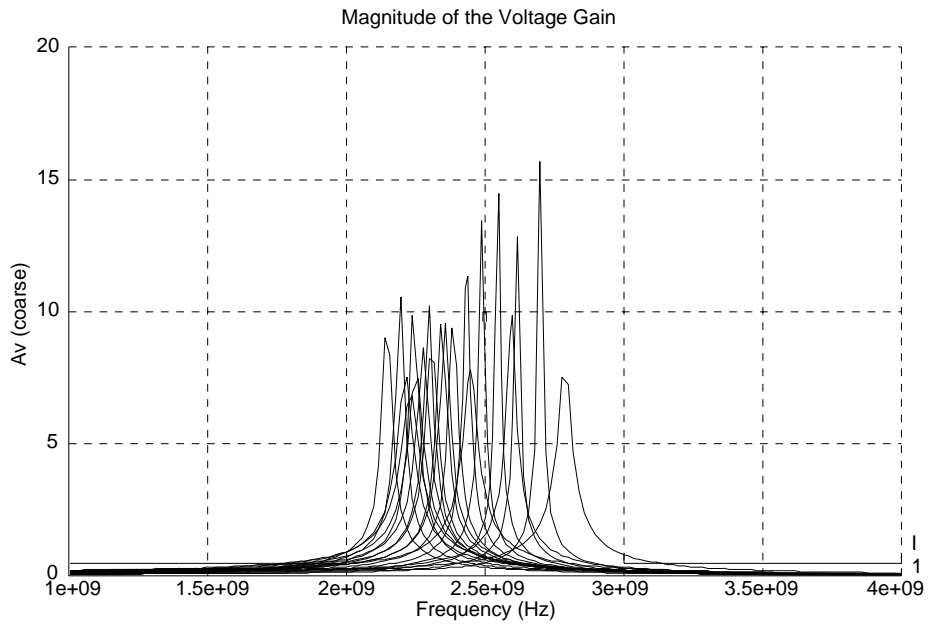


Fig. 5 Response of the coarse model in Fig. 4a before optimization.

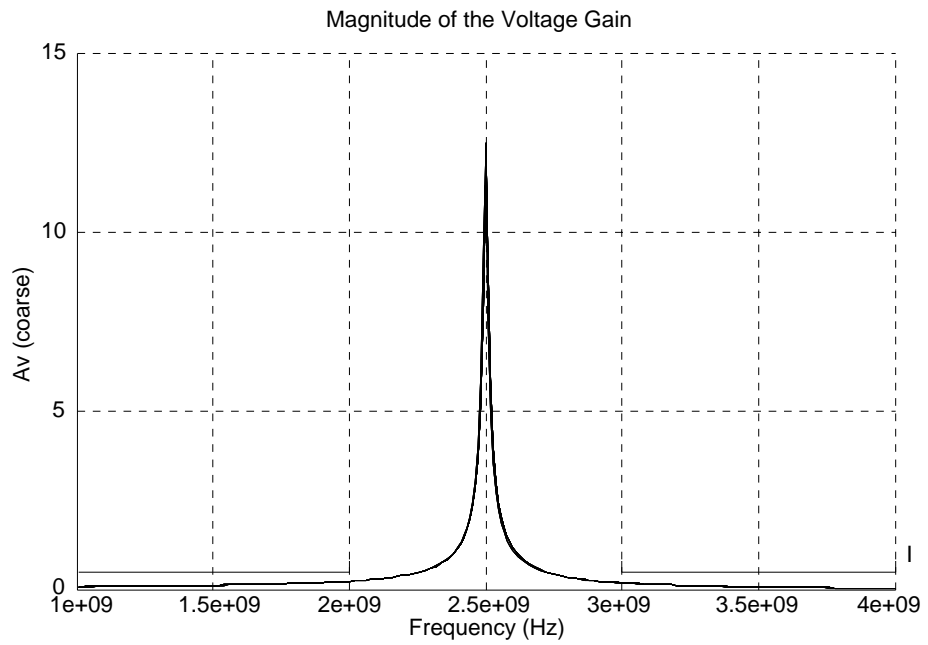


Fig. 6 Optimal coarse response (circuit in Fig. 4a).

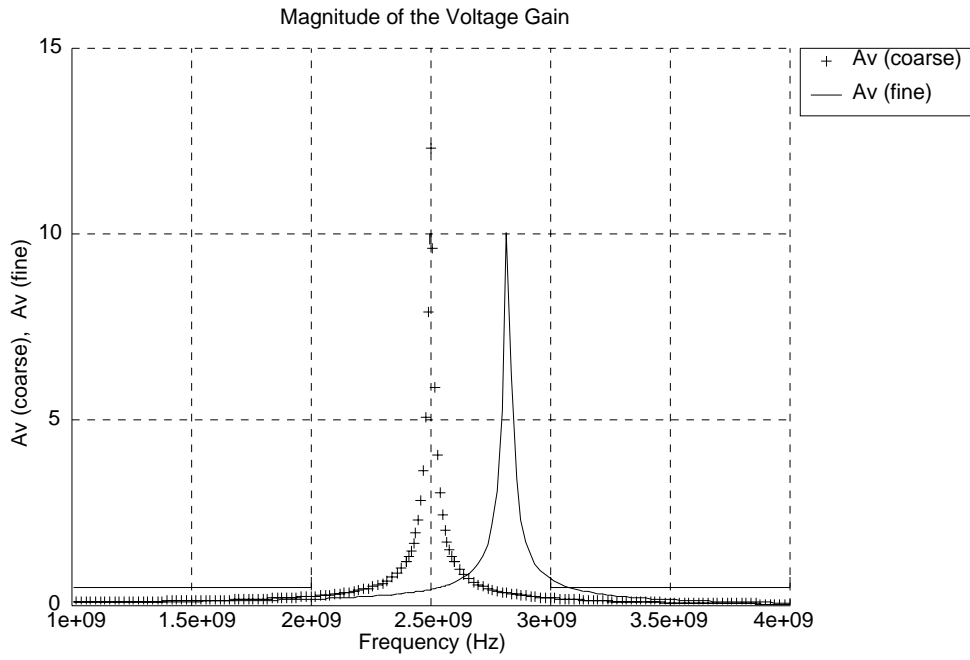


Fig. 7 Coarse and fine responses at the optimal coarse solution (Fig. 4).

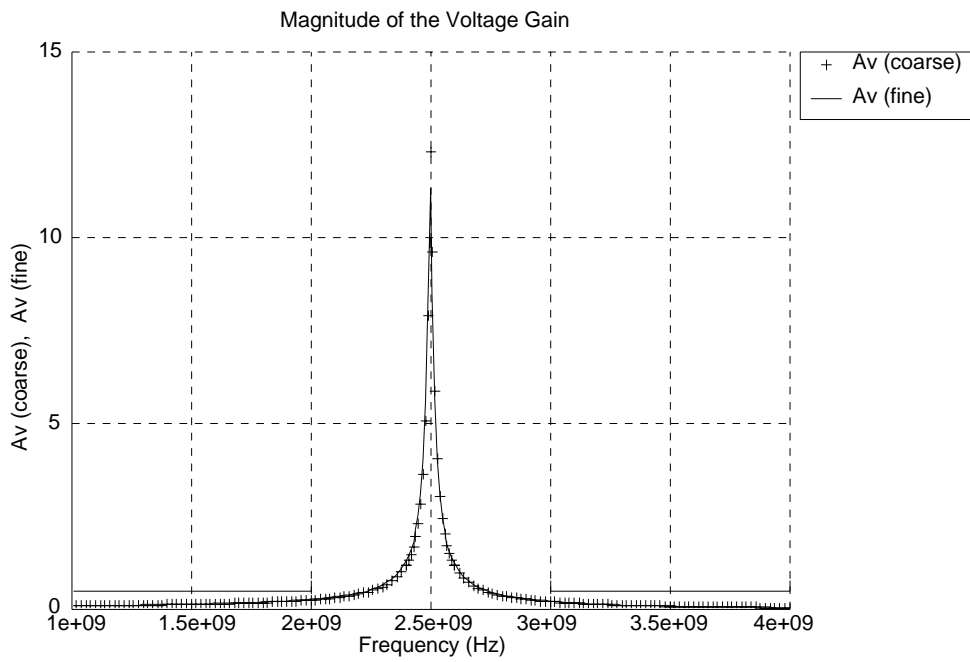


Fig. 8 Coarse and fine responses after SM optimization (Fig. 4).

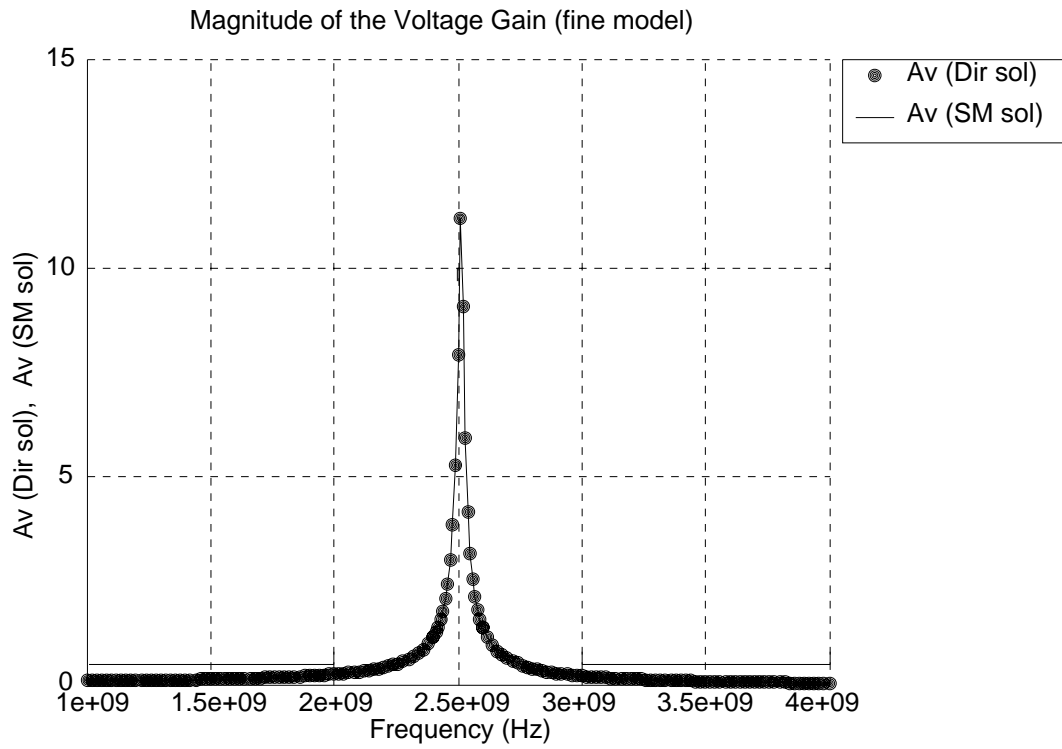


Fig. 9 Optimal fine responses: SM and direct solutions (Fig. 4).

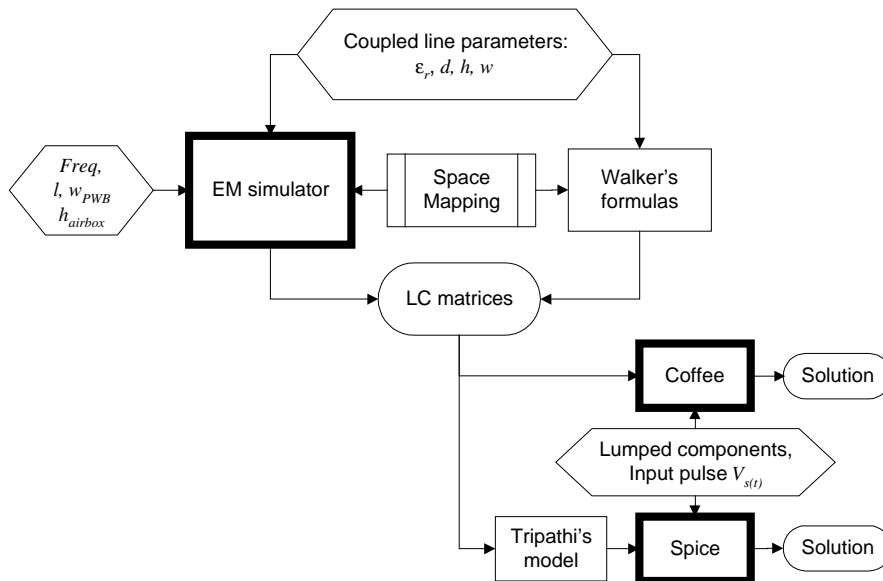


Fig. 10 Simulation flow of a crosstalk problem with a time domain approach.

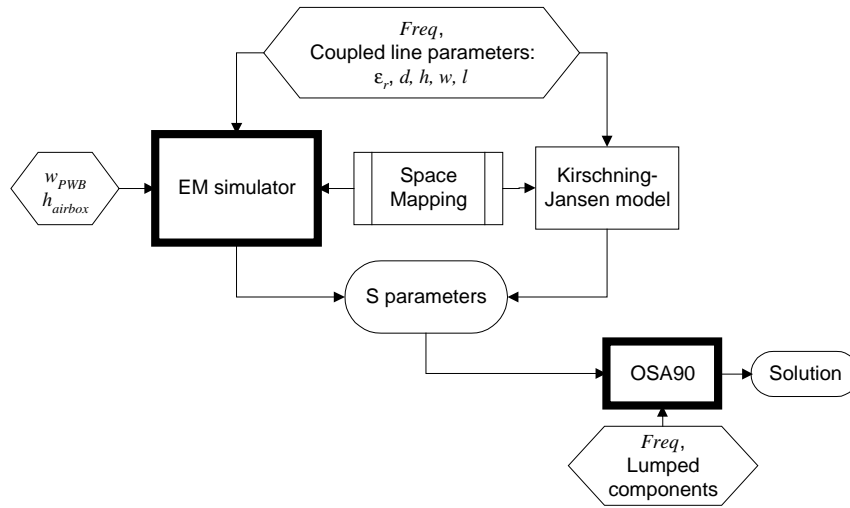


Fig. 11 Simulation flow of a crosstalk problem with a frequency domain approach.

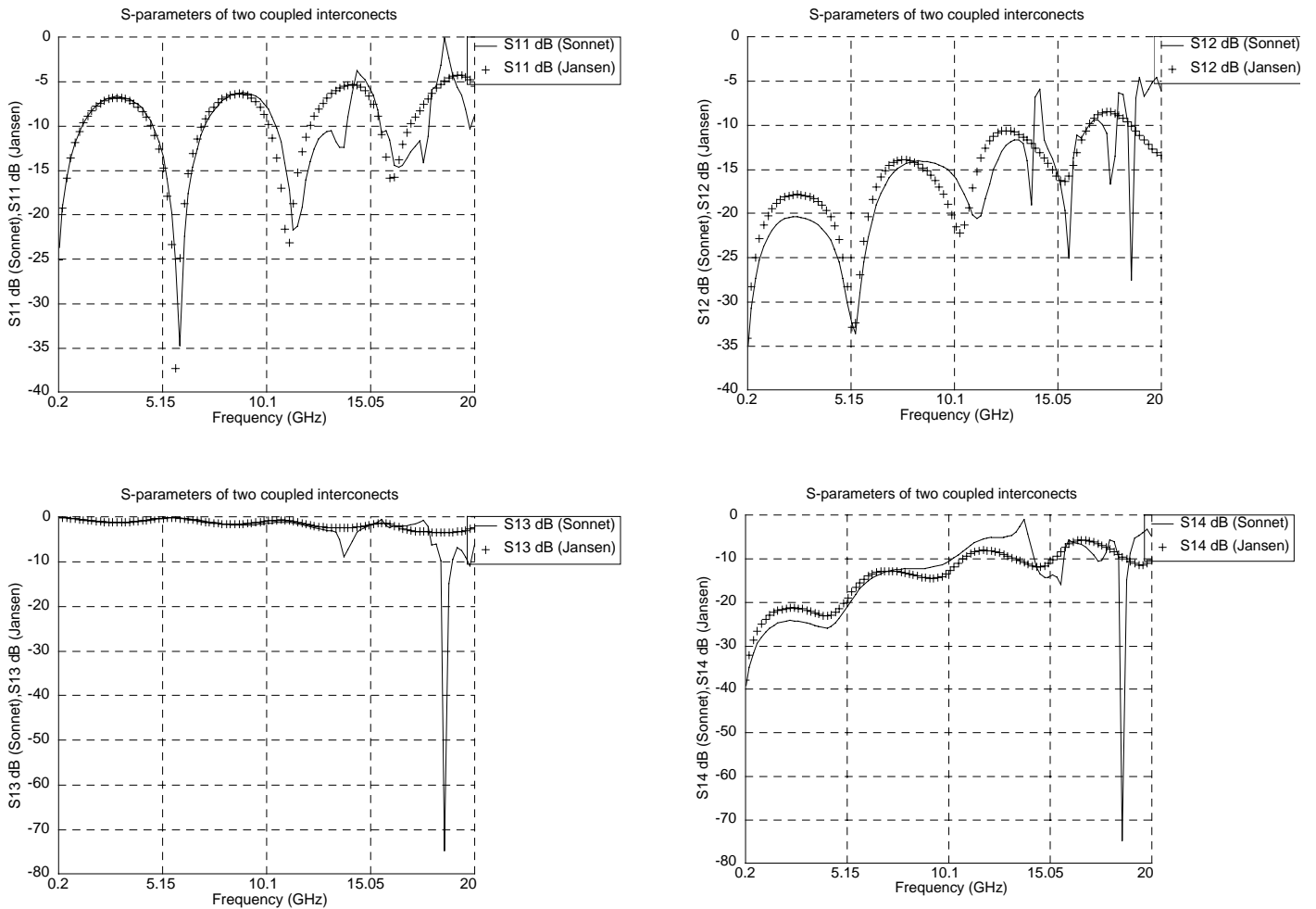


Fig. 12 Comparison between Sonnet's and Jansen's models for two coupled microstrips.

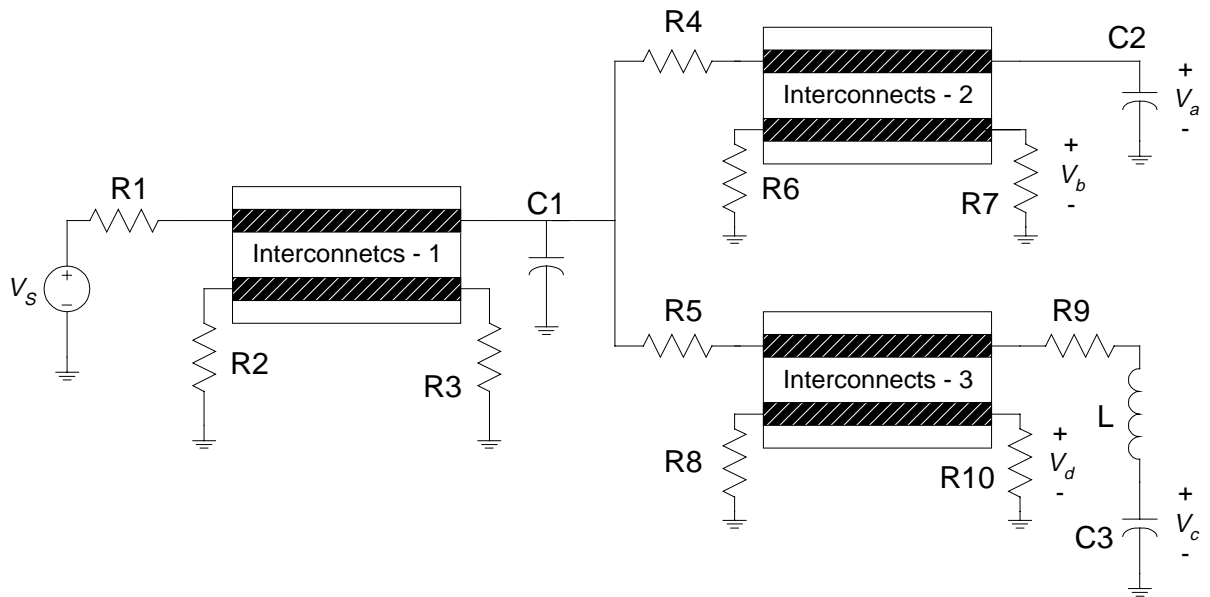


Fig. 13 Crosstalk minimization problem.

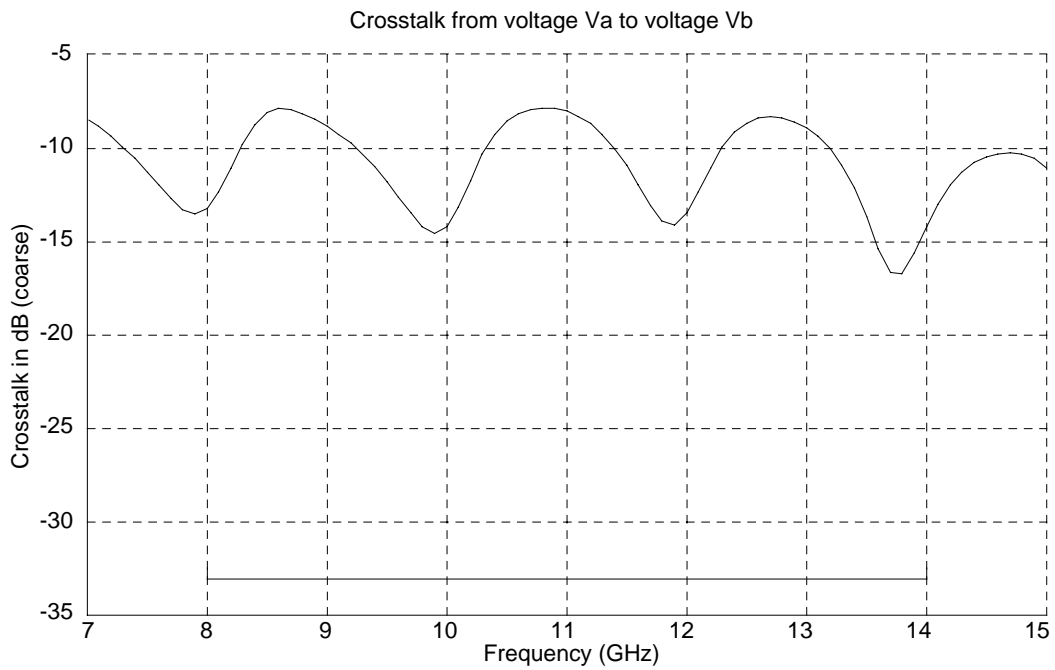


Fig. 14 Coarse response before optimization (circuit in Fig. 13).

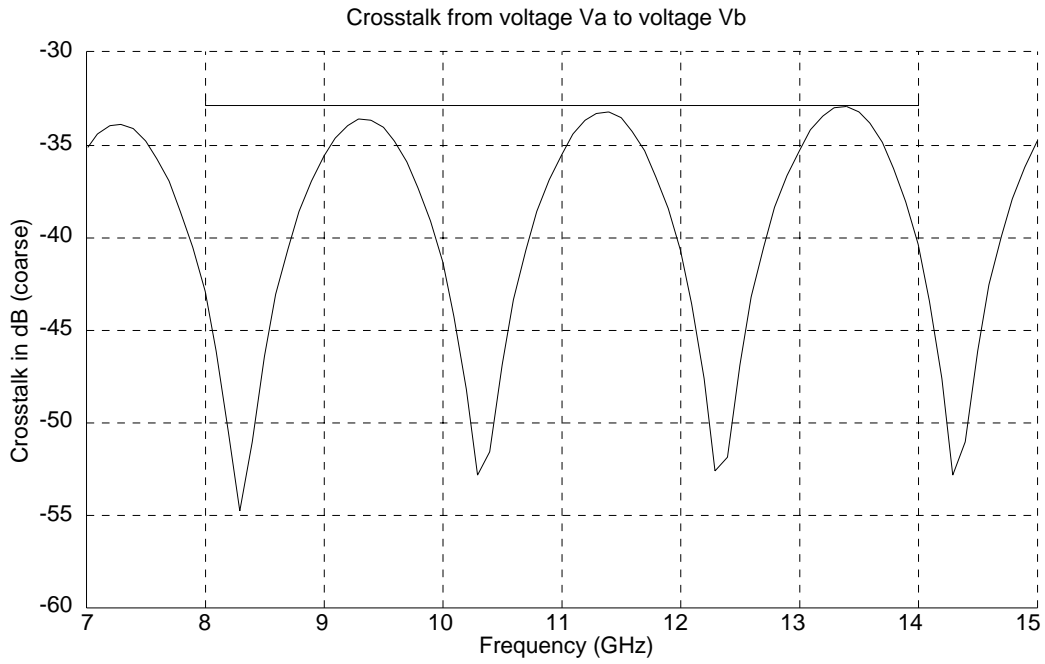


Fig. 15 Optimal coarse response (circuit in Fig. 13).

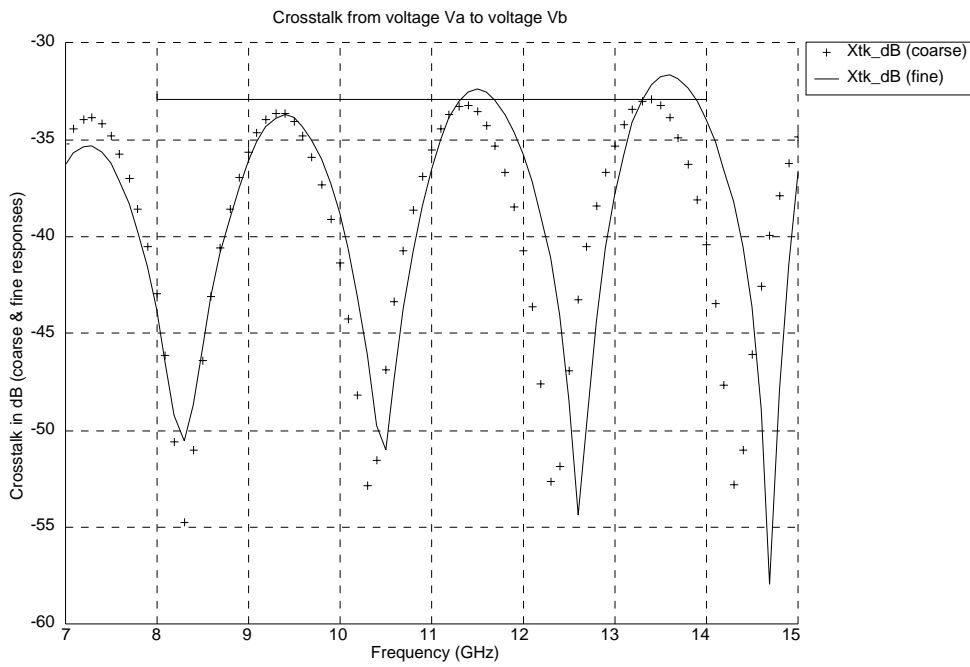


Fig. 16 Fine and coarse responses at optimal coarse solution (circuit in Fig. 13).

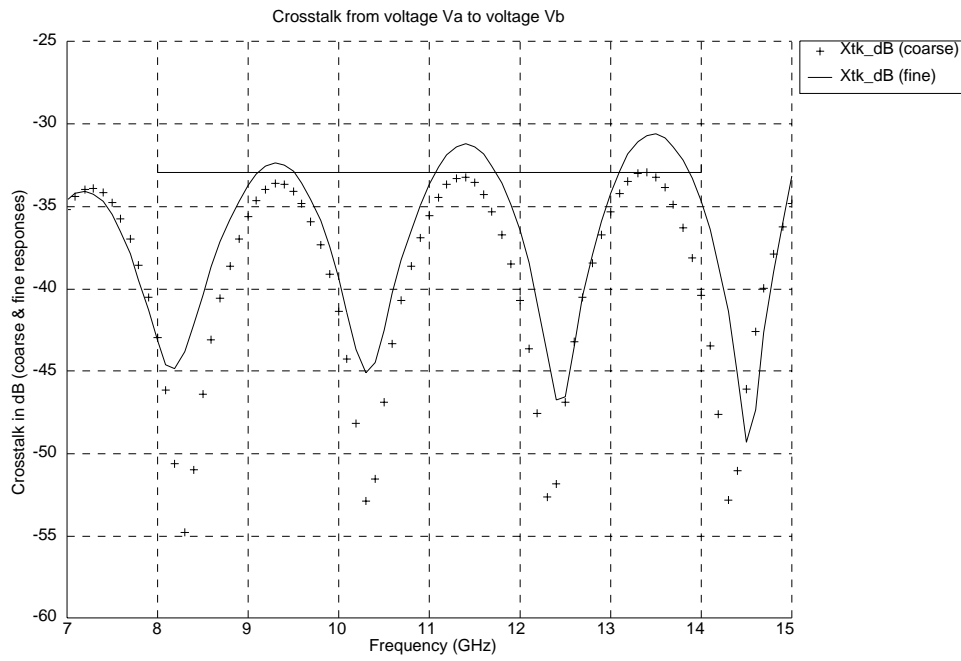


Fig. 17 Fine and coarse responses at optimal SM solution for the case when the real and imaginary parts of S_{11} and S_{12} were chosen as matching goals.

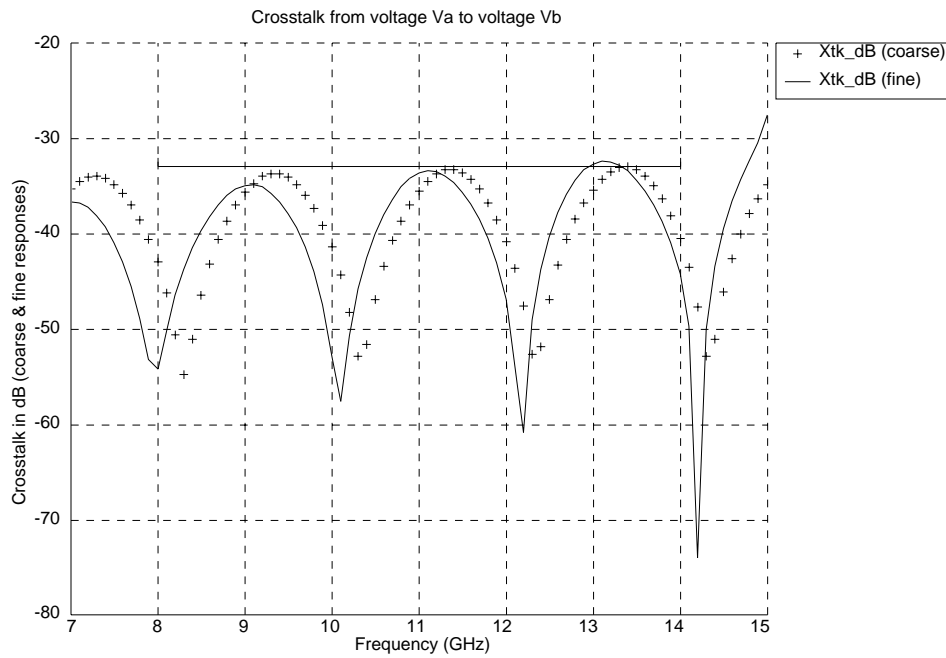


Fig. 18 Fine and coarse responses at optimal SM solution for the case when the crosstalk expression is used as the matching function and weighting factors are introduced.