OPTIMIZATION OF AN INHOMOGENEOUS TWO-SECTION WAVEGUIDE TRANSFORMER

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The problem of designing waveguide impedance transformers has been of practical interest from the very early years of microwave technology. Such structures provide broadband matching of waveguides operating in the same dominant mode H_{01}. In the past, the complexity of these structures required analytical approximations to be applied for design purposes. Major contributors to this field are Leo Young, George Matthaei and H. J. Riblet who proposed design formulas for quarter-wavelength multisection impedance transformers.

One of the first applications of direct optimization using computers to improve the performance of stepped waveguide transformers has been presented by Bandler [1]. The results published in [1] were used to set up the present optimization example of a two-section waveguide transformer between two waveguides with identical heights but different widths.

Example Overview

The *k*th section of a stepped inhomogeneous waveguide transformer is characterized by its width, a_k, height, b_k, and length, l_k (see Fig. 1). Here, the subscript k=1,2... denotes the section number. In the case of a two-section transformer Young shows that the optimal design is uniquely defined if either a_1 or a_2 is specified [2]. It therefore seems appropriate to fix the widths of the two sections and optimize only their heights and lengths. We carry out this process in the following presentation, although including the widths as variables could also be considered.

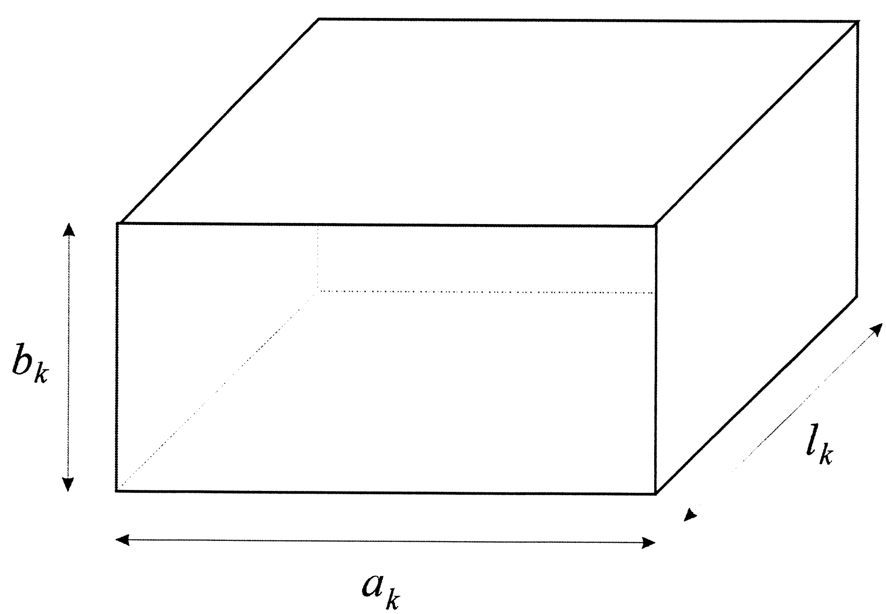


Fig. 1. A typical waveguide section.

In the following example the nominal file of the structure was created using the initial dimensions (before optimization) given in [1], which correspond to Young's design of a two-section transformer [2]:

TABLE 1

THE DIMENSIONS IN CM OF YOUNG'S TWO SECTION TRANSFORMER BEFORE OPTIMIZATION

	a, cm	*b*, cm	*l*, cm
Section 0 (input)	2.286	1.016	*Infinity*
Section 1	2.159	1.11	1.53312
Section 2	1.95834	1.03886	2.03877
Section 3 (output)	1.905	1.016	*Infinity*

This transformer was optimized by Bandler[1] for the frequency band from 8.16 GHz to 9.25 GHz using a minimax approach. Bandler's results produced a maximum VSWR of 1.047, which corresponds to a reflection coefficient $|S_{11}| = 0.023$.

The Nominal and Perturbed Projects

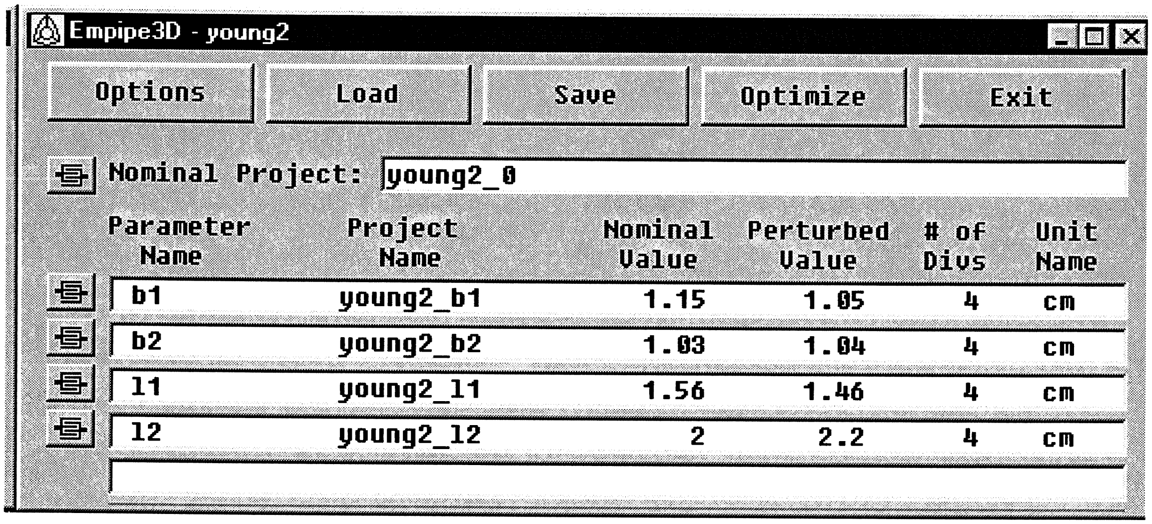
The selected nominal and perturbed values of the optimization variables are given in Table 2.

TABLE 2

NOMINAL AND PERTURBED VALUES OF THE OPTIMIZATION VARIABLES

<table>
<tr><th></th><th>a, cm</th><th colspan="2">b, cm</th><th colspan="2">l, cm</th></tr>
<tr><td>Section 0 (input)</td><td>2.286</td><td colspan="2">1.016</td><td colspan="2">1.6</td></tr>
<tr><td>Section 1</td><td>2.159</td><td>1.15</td><td>1.05</td><td>1.56</td><td>1.46</td></tr>
<tr><td>Section 2</td><td>1.95834</td><td>1.03</td><td>1.04</td><td>2</td><td>2.2</td></tr>
<tr><td>Section 3 (output)</td><td>1.905</td><td colspan="2">1.016</td><td colspan="2">1.6</td></tr>
</table>

The nominal and perturbed values of heights *b* and lengths *l* were chosen to be close to the values of Young's design and so that reasonable interpolation intervals could be set. Since Young's design was expected to be very close to the optimal solution, small perturbations were used. These values are well seen in the basic Empipe3D Geometry Capture form editor (Fig. 2).



Empipe3D - young2

Options | Load | Save | Optimize | Exit

Nominal Project: young2_0

Parameter Name	Project Name	Nominal Value	Perturbed Value	# of Divs	Unit Name
b1	young2_b1	1.15	1.05	4	cm
b2	young2_b2	1.03	1.04	4	cm
l1	young2_l1	1.56	1.46	4	cm
l2	young2_l2	2	2.2	4	cm

Fig. 2. Empipe3D Geometry Capture form editor showing the values of the nominal and perturbed dimensions.

Notice that the project subdirectories relevant to this example are

young2	working project automatically created by Empipe3D
young2_opt	parameterization files and database
young2_0	nominal project
young2_b1	incremental project for height of section 1
young2_b2	incremental project for height of section 2
young2_l1	incremental project for length of section 1
young2_l2	incremental project for length of section 2

Optimization Variables and Specifications

All four parameters are selected as optimization variables. Starting values, lower and upper bounds are set up in the Empipe3D Select Variables window (Fig. 3).

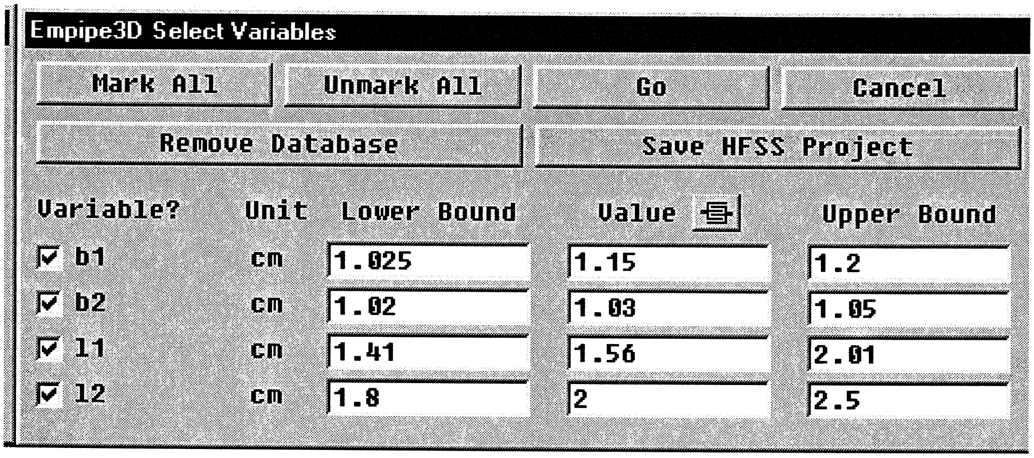


Fig. 3. The Empipe3D Select Variables window showing the nominal values and the bounds of the four optimization parameters.

To complete the setup of the optimization problem, the optimization goal has to be specified in the Empipe3D Specifications window (see Fig. 4). Notice that the weighting factor is set to 1. The frequency band is chosen as 8.16 GHz to 9.26 GHz for convenience to match the frequency sweep step.

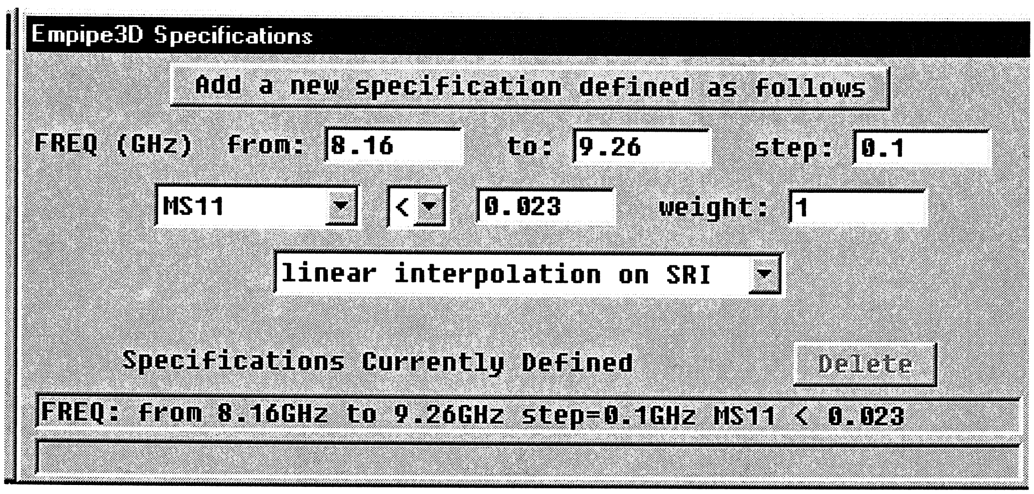


Fig. 4. The Empipe3D Specifications window and specifications for $|S_{11}|$ in the passband.

The Nominal Project and its Response

The solid model of the nominal structure is shown in the HP HFSS window (Fig. 5). This also represents the starting point in this example. Note that we could have invoked the HP HFSS Viewer by clicking the  button. Only half the structure is seen because we set up a *Perfect H Boundary*.

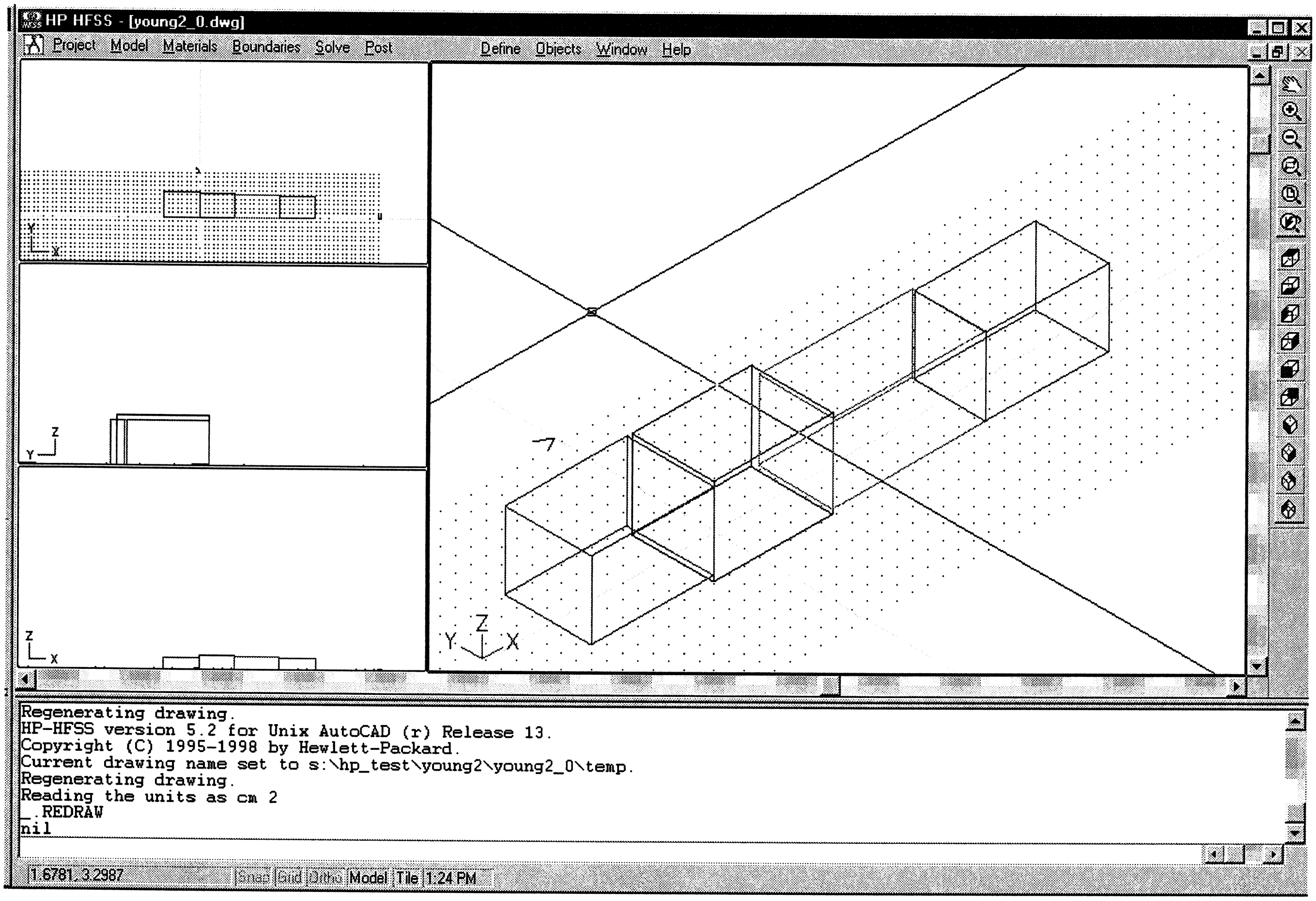


Fig. 5. The solid model of the nominal project as viewed in the HP HFSS window.

The nominal project *young2_0* is copied to a new project *young2_nom_sweep*. A preliminary frequency sweep in the broader frequency band 8 GHz to 9.4 GHz was performed for the nominal structure. The results for $|S_{11}|$ are displayed in the HP HFSS Postprocessor window as shown in Fig. 6.

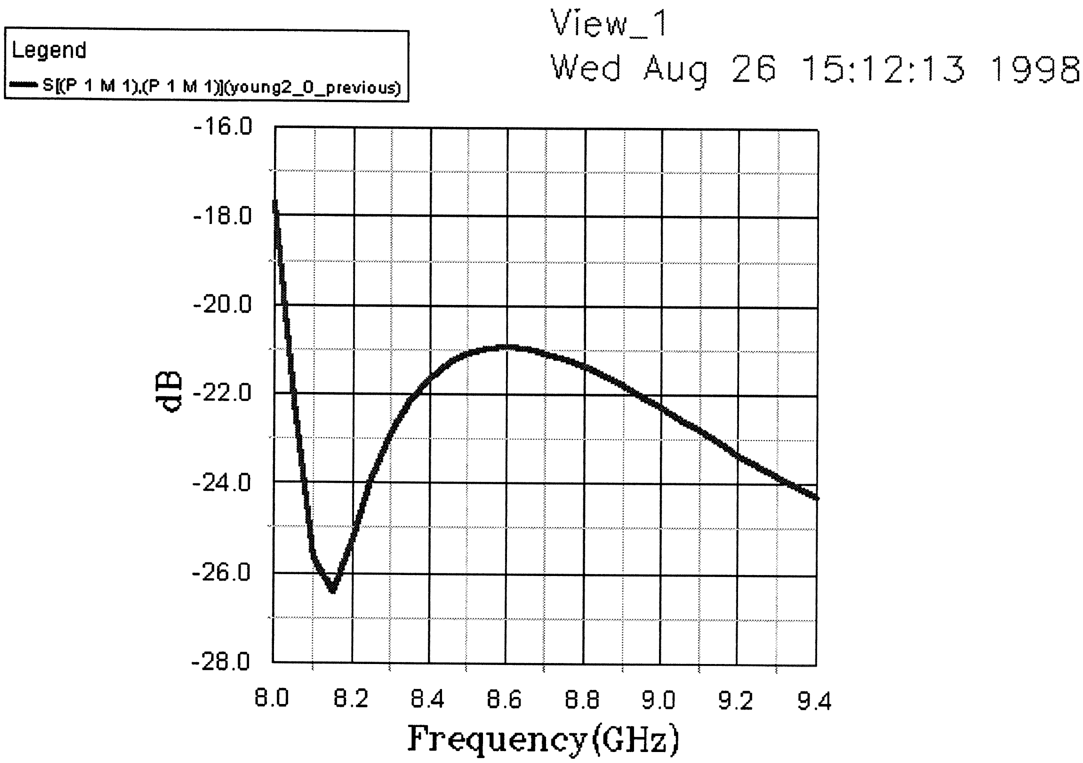


Fig. 6. HP HFSS output for $|S_{11}|$ in dB for the nominal two-section transformer structure.

Optimization Results

Unless otherwise stated default parameter settings for the Empipe3D sweep and optimization processes were selected.

The response of the nominal structure (starting point of optimization) can be viewed directly from the Empipe3D environment in the specified frequency range from 8.16 GHz to 9.26 GHz. After the netlist file is automatically generated by Empipe3D, a display frequency sweep is invoked. After the sweep is completed the results are fed back from HP HFSS to Empipe3D and displayed as shown in Fig. 7.

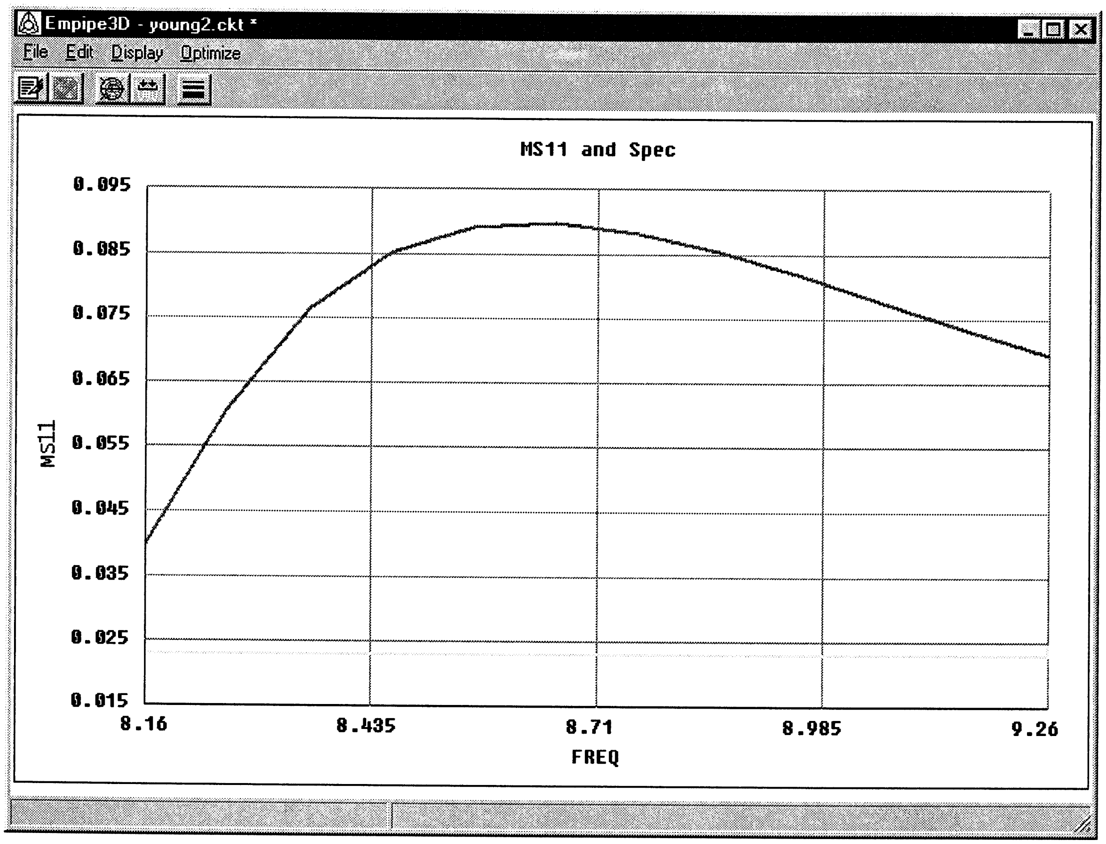


Fig. 7. $|S_{11}|$ and specifications before optimization.

The minimax optimizer was invoked. A significantly improved $|S_{11}|$ response was obtained in the frequency band of interest, as shown in Fig. 8.

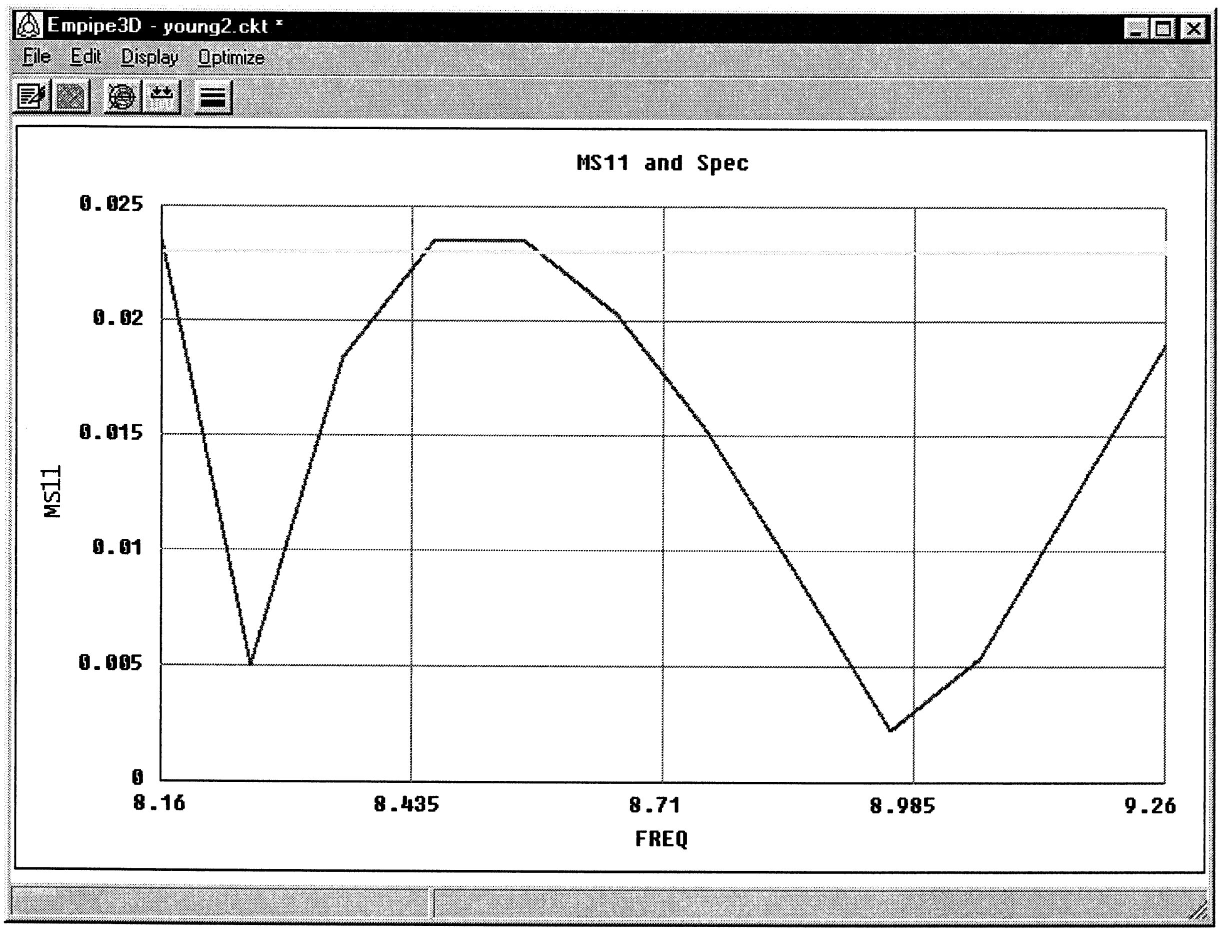


Fig. 8. $|S_{11}|$ and specifications after optimization.

The optimization report in Fig. 9 shows the progress of the objective function during the minimax optimization process. A second run of the minimax optimizer was invoked using the results of the previous optimization as a starting point. This time only eight iterations took place and they confirmed the solution found during the first optimization process. The second optimization report is shown in Fig. 10. There is a slight difference between the reported final value of the objective function corresponding to each of the two optimization processes. Nevertheless, the optimized parameters have not changed, which can be seen in the *Trace* block of the second optimization (see Fig. 11).

After the optimization is completed the netlist file (Fig. 11) is updated to report the optimized variables and the trace of their evolution during the optimization process. The optimized values are also automatically assigned as nominal values in the Empipe3D Select Variables window after exiting the netlist file editor (see Fig. 12).

By making use of the Geometry Capture feature of Empipe3D the optimized project was automatically generated by clicking the  button in the Empipe3D Select Variables window after exiting the Empipe3D netlist file editor. This project's subdirectory is *young2_opt_sweep*. A broader frequency band sweep was performed from 8 GHz to 9.4 GHz using HP HFSS directly after leaving Empipe3D completely. The $|S_{11}|$ response in dB generated by HP HFSS is shown in Fig. 13. This allows a validation to be made rather than relying on the interpolated response which would have been displayed through Empipe3D.

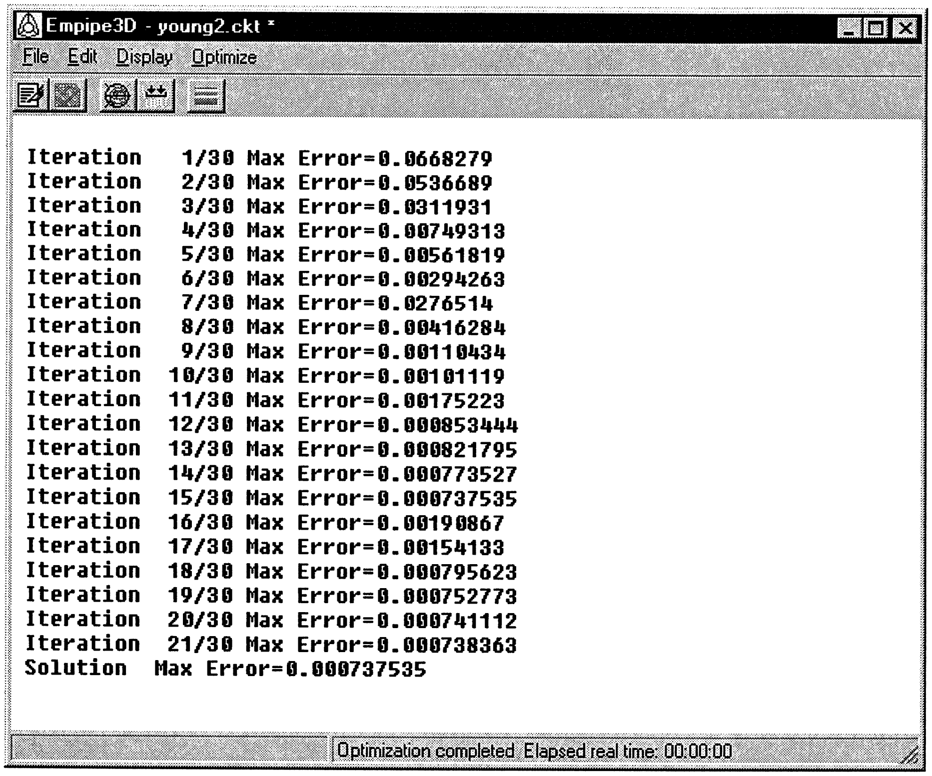


Fig. 9. The Empipe3D optimization iterations report.

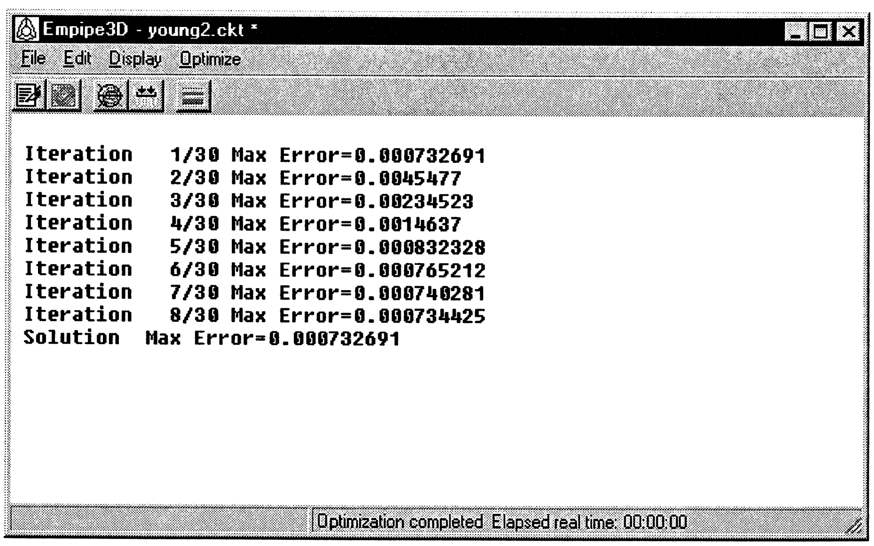


Fig. 10. The second Empipe3D optimization iterations report.

```
! Empipe3D user-defined structure YOUNG2
!  Sat Sep 19 09:54:15 1998. Minimax Optimizer. 21 Iterations. 00:00:00 CPU.
!  Sat Sep 19 10:04:40 1998. Minimax Optimizer. 8 Iterations. 00:00:00 CPU.
Model
#include "young2_opt\young2.inc";

   YOUNG2_b1: ?1.025 1.0874 1.2?;
   YOUNG2_b2: ?1.02 1.0489 1.05?;
   YOUNG2_l1: ?1.41 1.55009 2.01?;
   YOUNG2_l2: ?1.8 2.05697 2.5?;

   YOUNG2  1 2 0  model=7
      b1=(YOUNG2_b1 * 1cm)  b2=(YOUNG2_b2 * 1cm)
      l1=(YOUNG2_l1 * 1cm)  l2=(YOUNG2_l2 * 1cm);
   PORTS 1 0 2 0;
   CIRCUIT;

   MS_DB[2,2] = if (MS > 0) (20 * log10(MS)) else (NAN);
end
Sweep
   AC: FREQ: from 8.16GHz to 9.26GHz step=0.1GHz MS11
      {XSWEEP title="MS11 and Spec" X=FREQ Y=MS11
       SPEC=(from 8.16GHz to 9.26GHz, < 0.023)};

   AC: FREQ: from 8.16GHz to 9.26GHz step=0.1GHz MS MS_DB PS
  {Smith MP=(MS11,PS11).S11 title="Smith Chart S11"}
   {Polar MP=(MS21,PS21).S21 title="Polar Plot S21"};
end

Spec
   AC: FREQ: from 8.16GHz to 9.26GHz step=0.1GHz MS11 < 0.023;
end

Trace
 1.0874 1.0489 1.55009 2.05697
 1.08657 1.04031 1.55472 2.05493
 1.08719 1.04676 1.55126 2.05645
 1.08734 1.04838 1.5504 2.05683
 1.08736 1.04877 1.55017 2.05694
 1.08736 1.04889 1.5501 2.05697
 1.08739 1.0489 1.55009 2.05697
 1.0874 1.0489 1.55009 2.05697
end
```

Fig. 11. The netlist file after the two optimization processes are completed.

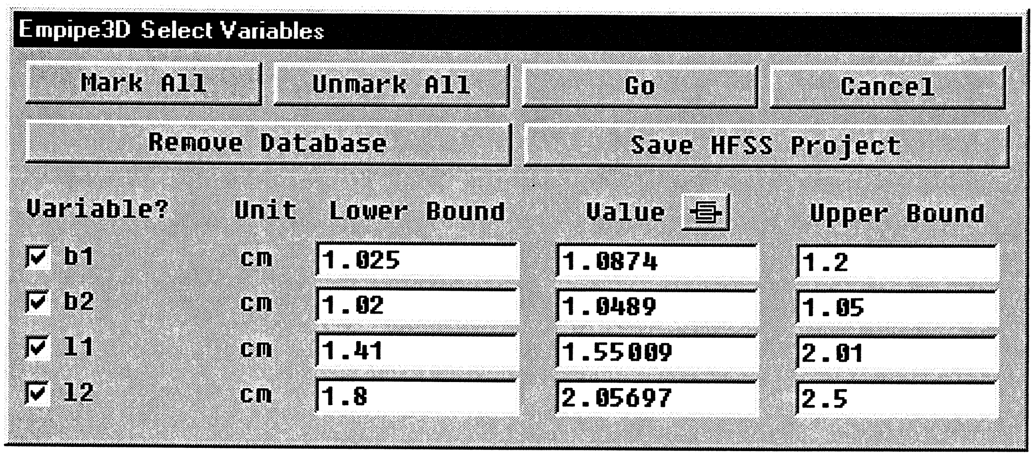


Fig. 12. The Empipe3D Select Variables window after optimization showing the final optimized parameter values.

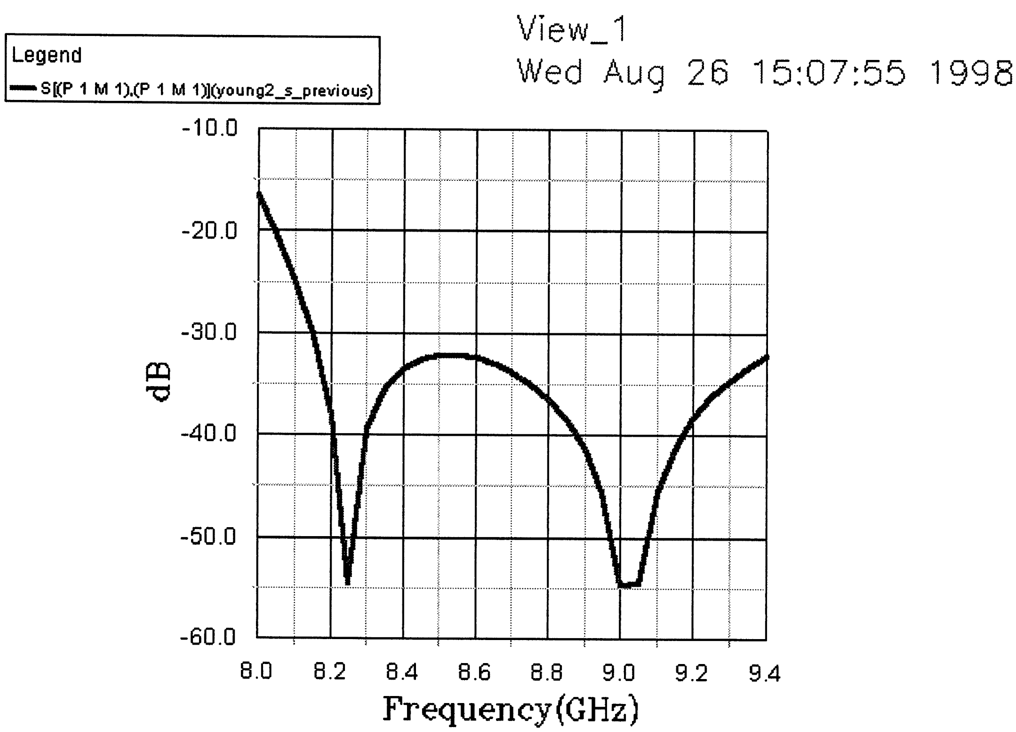


Fig. 13. HP HFSS output for $|S_{11}|$ in dB for the optimized two-section transformer structure.

References

[1] J.W. Bandler, "Computer optimization of inhomogeneous waveguide transformers," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-17, pp. 563-571, 1969.

[2] L. Young, "Inhomogeneous quarter-wave transformers of two sections," *IRE Trans. Microwave Theory Tech*, vol. MTT-8, pp. 645-649, 1960.