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ABSTRACT: In this technical report, the design of a high-frequency matching circuit is presented. This circuit is a transformer comprising a cascade of multisections of quarter-wavelength transmission lines. The transformer, also referred to as matching circuit, is implemented based on microstrip technology. The matching circuit is required to perform as a transition from a 10-Ω load to a 50-Ω source. Moreover, this transition is specified to have a return loss more than 20 dB over the entire S-band from 2 GHz to 4 GHz. Analytical model developed and verified by full-wave simulation results indicates that the design of a quarter-wavelength transformer with four sections satisfies required design specifications. In-house prototype unit is fabricated to validate design performance. The experimental and simulation results of microwave scattering parameters are in very good agreement within an acceptable degree of error.

KEYWORDS: HFSS, Matching, Microstrip circuit, Quarter-wave transformer, Transmission line

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ABSTRACT

In this technical report, the design of a high-frequency matching circuit is presented. This circuit is a transformer comprising a cascade of multisections of quarter-wavelength transmission lines. The transformer, also referred to as matching circuit, is implemented based on microstrip technology. The matching circuit is required to perform as a transition from a 10-Ω load to a 50-Ω source. Moreover, this transition is specified to have a return loss more than 20 dB over the entire S-band from 2 GHz to 4 GHz. Analytical model developed and verified by full-wave simulation results indicates that the design of a quarter-wavelength transformer with four sections satisfies required design specifications. In-house prototype unit is fabricated to validate design performance. The experimental and simulation results of microwave scattering parameters are in very good agreement within an acceptable degree of error.

KEYWORDS: HFSS, Matching, Microstrip circuit, Quarter-wave transformer, Transmission line

I. INTRODUCTION

This work started as a project for the undergraduate class at Syracuse University: ***Fundamentals of Radio Frequencies and Microwaves***. The project objectives are to understand the basics of high-frequency circuits; to develop analytical skills essential for RF engineer; to learn how to use current commercial high-frequency simulation software packages for modeling purposes; and to go through the entire cycle of modeling, design, fabrication, and testing of high-frequency circuits in general and matching circuits in particular. To fulfill educational objectives, a challenging design of a high-frequency matching circuit is given. The matching circuit is required to perform as a transition between a 10-Ω load and a 50-Ω source. This transition is specified to have a return loss more than 20 dB over the entire S-band from 2 GHz to 4 GHz. Moreover, fabrication related issues such as tolerance, cost, and easiness are to be considered as design aspects.

To realize the goals set forth for the transition requirements, it is first necessary to formulate several design considerations. Several matching options are investigated such as single open-circuited stub, double open-circuited stub, and transformer comprising multisections of quarter-wavelength transmission lines. Based on preliminary performance, it is found that matching based on a multiple sections of quarter-wavelength transmission lines is expected to meet required design goals. These quarter-wavelength transmission lines are implemented in a microstrip technology. The first attempted design is to use a three-section quarter-wavelength transformer. It is found that a three section quarter-wave transformer cannot be configured to realize a 20-dB loss over the entire S-Band. This means that the order of transformer which is also referred to as matching circuit, has to be increased, i.e., design the circuit using four-sections or even more than four sections of quarter-wavelength transmission lines. Due to discontinuities and parasitic effects, the designed matching network circuit is optimized to meet given specifications. A prototype circuit is fabricated and tested. It is noted here that two high-frequency computer aided design (CAD) packages are used: Ansoft Designer [1] is used for circuit modeling and analysis; Ansoft HFSS [2] is used for final full-wave analysis and optimization.

II. CIRCUIT-BASED DESIGN

The design process begins with a series of analytical calculations aimed at determining an acceptable set of parameters for the lengths and widths of each quarter-wave section. The analytical calculations are obtained from the text books adopted for the class [3], [4]. The initial lengths and characteristic impedances are presented in Table 1. Those initial design values provide a good starting design that can be optimized for optimum performance. The equation used to find the initial impedances of each section is the following:

$$Z_Q = \sqrt{Z_{Q-}\, Z_{Q+}} \qquad (1)$$

where Z_Q is the characteristic impedance of the Qth transmission line as shown in Fig. 1 and it represents the matching section between the lines of characteristic impedances Z_{Q-1} and Z_{Q+1}. This equation is only valid for transformers with quarter-wavelengths.

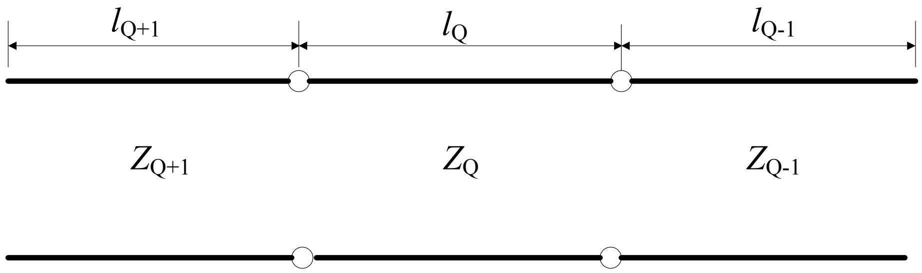

Fig. 1. Cascade of quarter-wavelength transmission lines with different characteristic impedances and lengths

The design methodology begins with a simplified approximation model for circuit elements and then generalizes the model by incorporating discontinuity effects such that it better corresponds to the actual physical realization of a circuit design. From engineering point of view, a design procedure is easier to start based on simplified assumptions and adding more realistic effects, in another word, the actual problem is broken into sub-problems which are much simpler to handle and faster to solve. Thus, the design of a matching network goes through few simple stages rather than going through a tedious optimization process of the actual complex problem. The design steps are explained as follows. First, the design starts by assuming ideal lossless transmission line model where each transmission line is only characterized by its real characteristic impedance and its corresponding electrical length at the center frequency of operational bandwidth. The schematic of ideal circuit analyzed in Ansoft Designer suite is given in Fig. 2. The ideal-circuit based initial frequency response presented in Fig. 3 corresponds to following characteristic impedance and electrical length values: $Z_1 = 41.8\ \Omega$, $Z_2 = 35\ \Omega$, $Z_3 = 29.31\ \Omega$, $Z_4 = 17.12\ \Omega$, $l_1 = 89°$, $l_2 = 93°$, $l_3 = 101°$, $l_4 = 115°$. It is obvious that initial response satisfies specs related to return loss only at the lower end of frequency response; however, return loss is deteriorated toward the upper end of bandwidth.

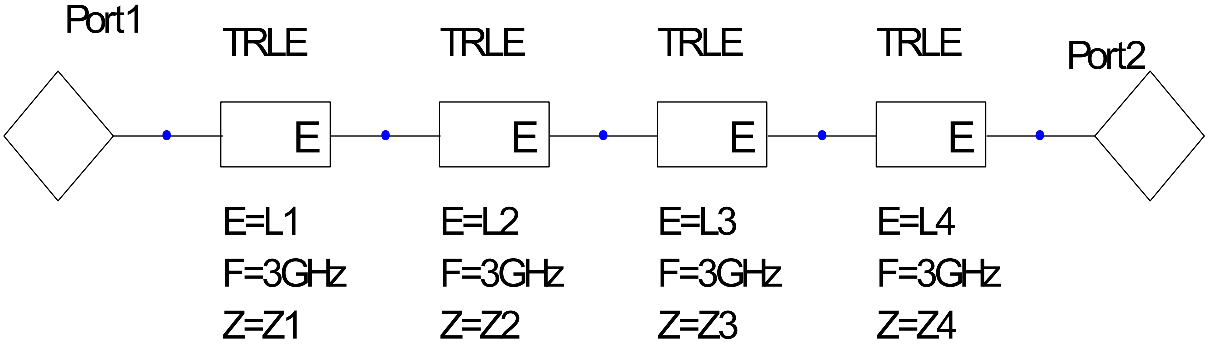

Fig. 2. Circuit schematic based on ideal lossless transmission lines characterized by their real characteristic impedances and electrical lengths in degree. Input port of impedance 50 Ω represents source impedance and output port of 10 Ω corresponds to load impedance.

Table 1. Initial design values for the electrical length and impedance of quarter-wave sections included in the ideal circuit shown in Fig. 2.

Section	1	2	3	4
Impedance (Ω)	$Z_1 = 41.8$	$Z_2 = 35.0$	$Z_3 = 29.31$	$Z_4 = 17.12$
Electrical length (deg)	$l_1 = 89$	$l_2 = 93$	$l_3 = 101$	$l_4 = 115$

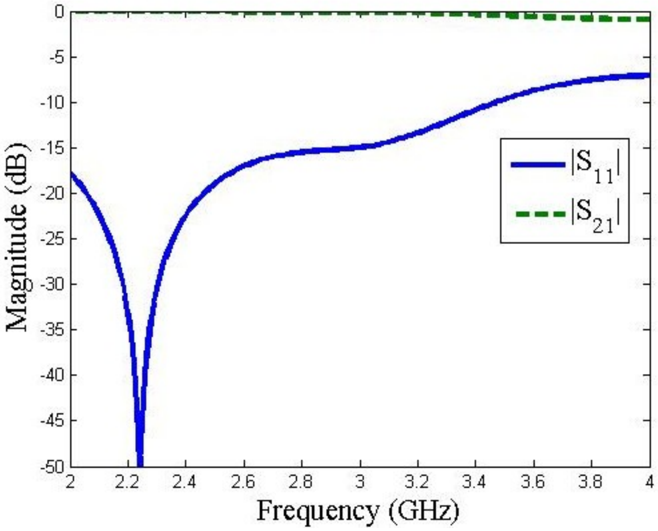

Fig. 3. The response of ideal circuit, shown in Fig. 2, corresponding to the initial values of length and characteristic impedance of quarter-wave transformer sections given in

Table 1. $Z_1 = 41.8\ \Omega$, $Z_2 = 35\ \Omega$, $Z_3 = 29.31\ \Omega$, $Z_4 = 17.12\ \Omega$. $l_1 = 89°$, $l_2 = 93°$, $l_3 = 101°$, $l_4 = 115°$.

At this point, the parameters of ideal circuit have to be modified to get a response satisfying specs requirements over the entire frequency band. A tuning process is carried out to in Ansoft Designer where electrical lengths are kept constant and only the values of characteristic impedances are tuned. Here, tuning refers to a special case of optimization where tuning variables are changed one at a time to improve frequency response. After few tuning steps, it is found that characteristic impedance values given in Table 2 produce a frequency response where return loss is below 25 dB over the entire bandwidth as shown in Fig. 4.

Table 2.Tuned values of characteristic impedances and lengths of ideal circuit model shown in Fig. 2.

Section	1	2	3	4
Impedance (Ω)	$Z_1 = 37.5$	$Z_2 = 22.1$	$Z_3 = 13.6$	$Z_4 = 10.7$
Electrical length (deg)	$l_1 = 89$	$l_2 = 93$	$l_3 = 101$	$l_4 = 115$

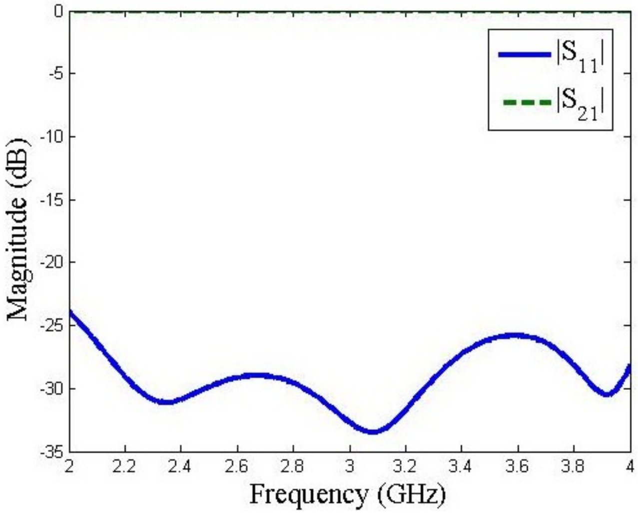

Fig. 4. Frequency response with the tuned values of characteristic impedances: $Z_1 = 37.5\ \Omega$, $Z_2 = 22.1\ \Omega$, $Z_3 = 13.6\ \Omega$, $Z_4 = 10.7\ \Omega$. Electrical lengths are kept the same as those given in Table 1.

III. PRACTICAL DESIGN METHODOLOGY

The second step in design is to do synthesis to find the actual physical width and length of each transmission line section that gives the characteristic impedance and electrical length values obtained in Table 2. So far, the circuit analysis does not require the determination of fabrication technology or the selection of a microwave substrate. However, the design is at a point where technology should be determined as well as fabrication material. For the purpose of this project, the main factor that controls proper selection is the minimum and maximum dimensions of trace widths that can be easily realized in the microwave lab at Syracuse University. Also, the availability of material is an important reason to decide upon material choice. The technology adopted for fabrication is based on microstrip due to the ease of fabrication and availability of manufacturing facility in the microwave lab. RT/duroid 6006 material from Roger's Corporation is the winning candidate for this current design application. It is a high frequency laminate which is Teflon-based filled with ceramic to obtain a high dielectric constant. RT/duroid 6006 is easy to fabricate and it has a tight dielectric constant [5]. The basic electrical properties and dimensions of the RT/duroid 6006 laminate are given in Table 3. Other mechanical and electrical properties can be found in [5].

Table 3. Properties of the Rogers 6006 laminate used in this experiment.

Dielectric Constant, ε_r	Loss tangent, tan δ	Dielectric thickness, h	Copper thickness, t
6.15± 0.15	0.0027	1.27 mm	0.017 mm

The schematic of microstrip-based circuit design is shown in Fig. 5 where the element 'MSSTEP' represents the discontinuity between microstrip lines with different widths. The corresponding response for this circuit is given in Fig. 6. The physical dimensions of microstrip lines, given in Table 4, are synthesized to produce the same electrical parameters in Table 2 obtained from design step based on circuit analysis. It is noted that in Table 4, the section labeled '0' represents a 50-Ω microstrip with a physical length equal to quarter wavelength at center frequency. This section is used to mimic the actual scenario of an existing 50-Ω microstrip line to which the SMA connector is attached.

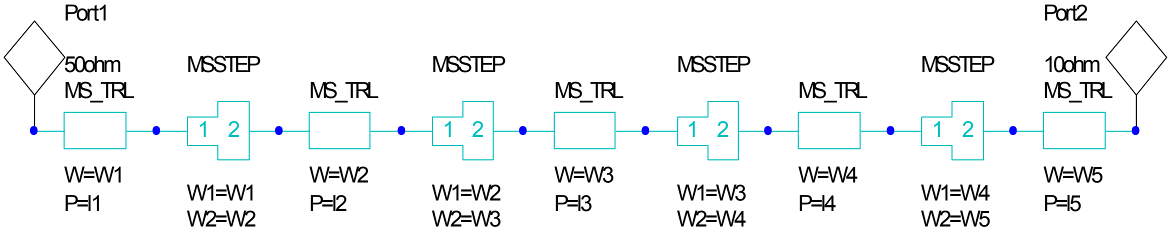

Fig. 5. Circuit schematic for microstrip-based circuit design. The effect of step discontinuity between transmission lines of different trace widths is modeled by including microstrip discontinuity MSSTEP. Substrate parameters are: $\varepsilon_r = 6.15$, tan $\delta = 0.0027$, $h = 1.27$ mm, $t = 0.017$ mm.

The frequency response of microstrip-based circuit has a return loss below 25 dB over the entire bandwidth. However, for better improvement, the microstrip is further tuned. The response for tuned microstrip design is shown in Fig. 7 and the corresponding values for the lengths and widths of the quarter-wave transformer sections are given in Table 5. It is noted that in Table 5, the section labeled '5' corresponds to the 10-Ω load.

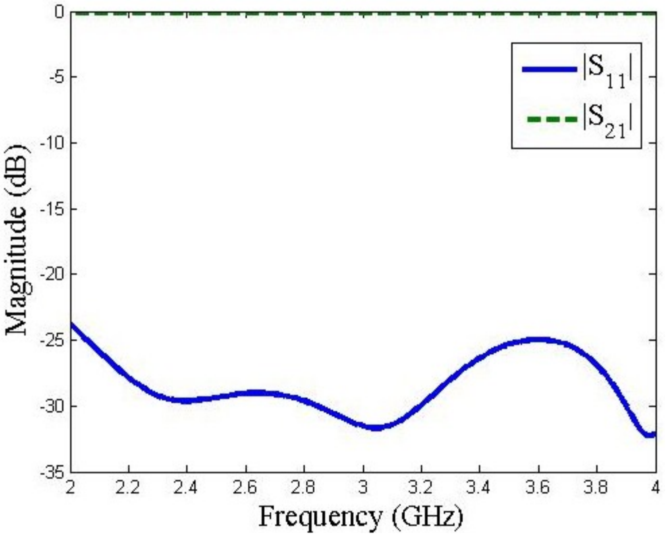

Fig. 6. Response for microstrip-circuit design based on the values of physical widths and lengths given in Table 4.

Table 4. Values for the lengths and widths of quarter-wave transformer sections realized in microstrip configuration. The physical values correspond to the electrical parameters, given in Table 2, obtained from circuit-based analysis.

Section	0	1	2	3	4
Width (mm)	1.83	2.98	6.32	11.61	15.43
Length (mm)	11.86	11.42	11.41	12	13.49

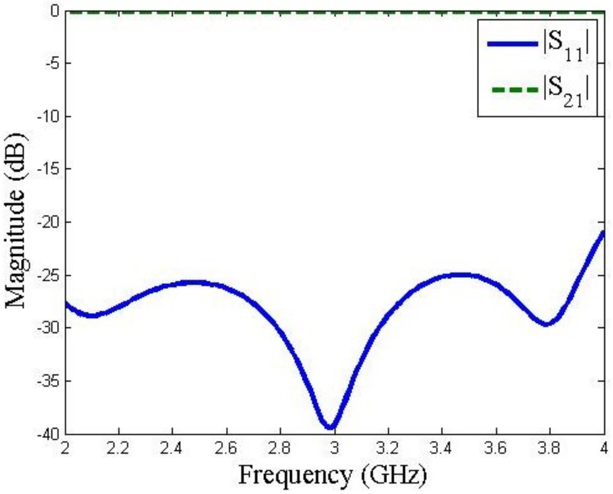

Fig. 7. The frequency response of tuned microstrip-based design using the values of physical widths and lengths given in Table 5.

Table 5. Values for the tuned lengths and widths of quarter-wave transformer sections realized in microstrip configuration.

Section	0	1	2	3	4	5
Width (mm)	1.83	2.98	6.34	11.65	15.49	16.68
Length (mm)	15.41	11.25	11.1	11.81	15.79	10.52

The circuit schematic in Fig. 5 utilizes an output port of 10 Ω to represent the load. For the purpose of transition characterization, a back-to-back transition is implemented such that both input and output ports have 50-Ω impedance [6]. It is noted that a 50-Ω system is used for measurements. Converting the design to a back-to-back configuration requires that the circuit be mirrored about the load such that the load is centered in the network and the rest of the circuit is symmetrical to either side and terminated in a 50- Ω section to which SMA connectors are soldered to have access to input and output. The schematic for this back-to-back configuration is shown in Fig. 8. The response for the back-to-back configuration is given in Fig. 9 where the values for impedance, length, and width of each section are the same as those given in Table 5.

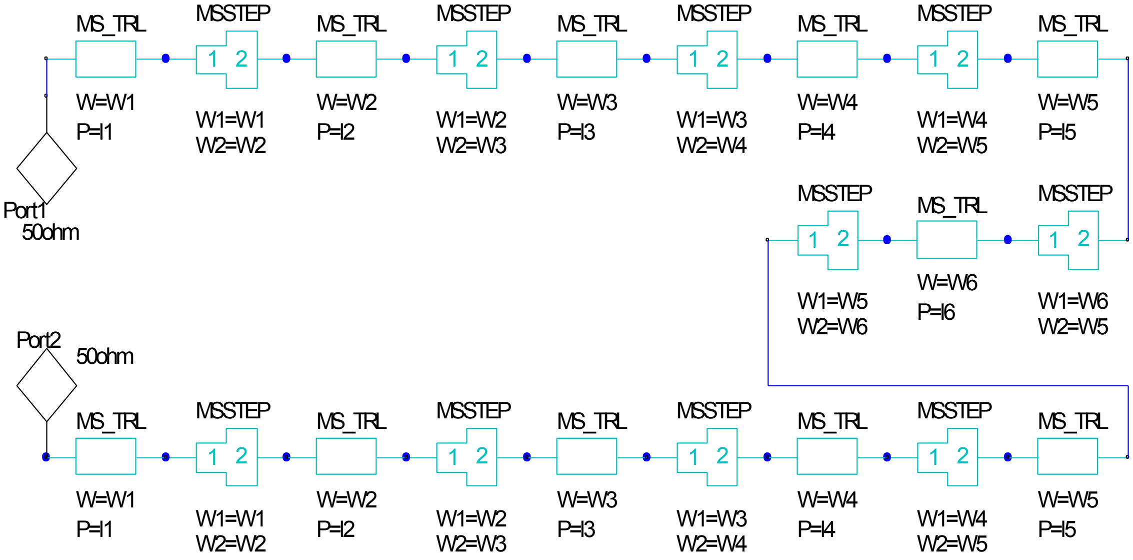

Fig. 8. Schematic for back-to-back microstrip-circuit transition.

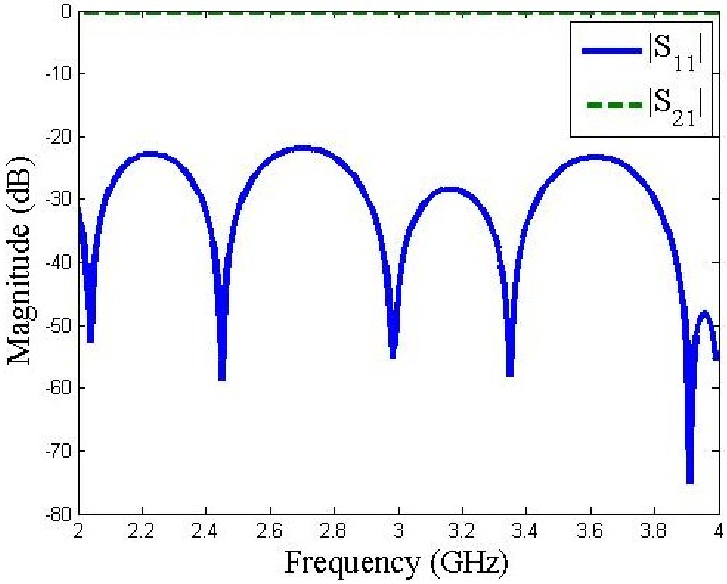

Fig. 9. The frequency response of the back-to-back microstrip circuit design shown in Fig. 8. The physical dimensions of lengths and widths given in Table 5 which correspond to the tuned lengths and widths of quarter-wave transformer sections realized in microstrip configuration are used to get this response using Ansoft Designer.

IV. FINAL DESIGN SIMULATION AND FABRICATION

The circuit-based simulation done with Ansoft Designer provides quickly design results. However, in order to predict accurately the final performance of actual physical circuit, the design is simulated with the full-wave solver Ansoft HFSS. As expected from previous experimentation using Ansoft Designer, the full-wave analysis yields a viable response with a return loss better than 20 dB over the entire frequency band from 2 to 4 GHz. The 3-D view of the back-to-back microstrip transition model used in HFSS is shown in Fig. 10. The HFSS simulation results of return loss and transmission given in Fig. 12 meet the design requirements.

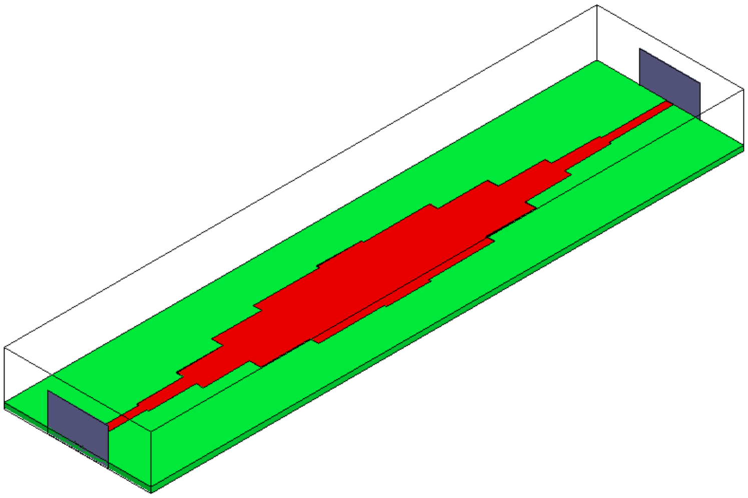

Fig. 10. 3-D view of the back-to-back microstrip transition model used for full-wave analysis in HFSS.

From this point, the fabrication process follows. First, a CAD drawing is made of the design using AutoCAD to produce the type of drawing file necessary to run the milling machine at the Syracuse University RF/Microwaves lab. After circuit fabrication, two 50-Ω SMA connectors are soldered at both ends of the circuit as shown in Fig. 11 to allow connection to vector network analyzer (VNA) to measure microwave scattering parameters and verify if the design meets the required specifications. Measurement results are included in Fig. 12 along with the simulation results. It can be seen from the graph that the design generally stays within a limit of 5 dB of the intended target return loss with the exception of frequencies at the higher end of the specifications from 3.8 to 4 GHz. There are clearly differences between the full-wave simulations and actual measurement results. These differences could be due to several reasons.

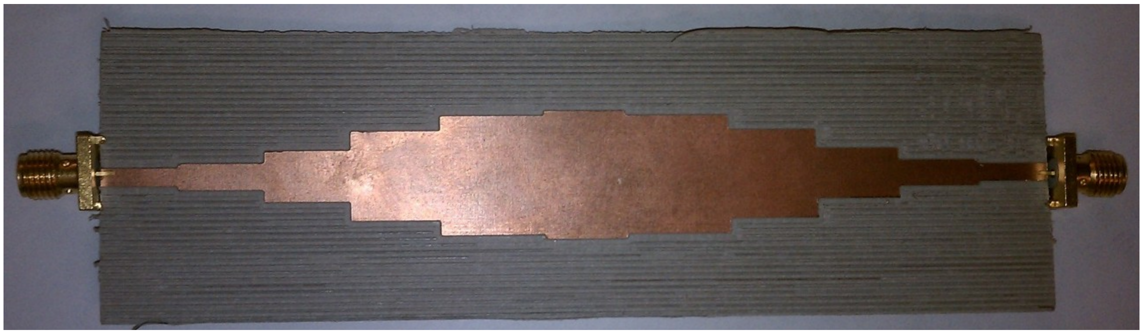

Fig. 11. Actual fabricated circuit.

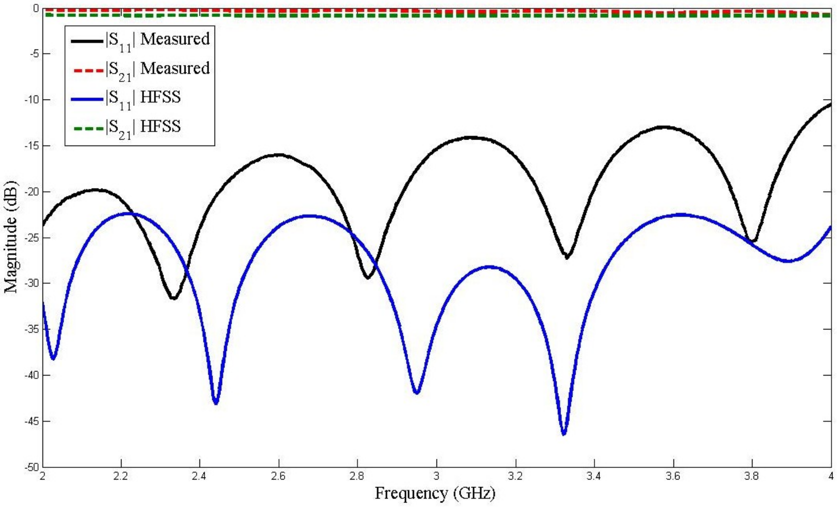

Fig. 12. Measured results in comparison with full-wave simulation results as obtained from HFSS for the back-to-back microstrip transition. Dimensions of circuit design.

First, the simulation did not account for the SMA connectors at both ends of the circuit. Second, the soldered connections from the microstrip to the SMA connectors were not the best. This could be largely in part due to the fact that the solder does not stick well to copper and there were no means of coating the microstrip in the lab. Also, there were many problems with the tools in the lab. As can be seen in the photograph of Fig. 11, it appears that the CNC machine etched too far into the surface of the microstrip design possibly causing even more flaws that could account for the inconsistencies between simulation and fabrication results.

CONCLUSIONS

In this technical report, the design methodology of a microstrip transition is presented. The transition is required to have a 20-dB return loss over the entire S-band from 2 GHz to 4 GHz. The design modeling went through two phases. First phase is circuit based to get quick results and second is the full-wave analysis of actual physical structures. The fabrication and experimental results are in good agreement.

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