JJEE
Volume 3, Number 3, 2017
Pages 171-180
Jordan Journal of Electrical Engineering
ISSN (Print): 2409-9600, ISSN (Online): 2409-9619

Design of Compact Impedance Matching Components

Ala'a I. Hashash[a], Mohammed H. Bataineh[b], Asem Sh. Al-Zoubi[c]

Department of Telecommunications Engineering, Yarmouk University, Irbid, Jordan
[a]e-mail: alazam_alaa@yahoo.com
[b]e-mail: mohbat@yu.edu.jo
[c]e-mail: asem@yu.edu.jo

Received: July 8, 2017 *Accepted: September 21, 2017*

Abstract— In this paper, compact impedance matching components are designed. Impedance matching of quarter wave, binomial, Chebyshev, and tapered transformers are considered. These are designed first by using uniform microstrip lines. Then these structures are compacted by imposing nonuniformity in the lines. The characteristic impedance of the nonuniform transmission line (NUTL) is presented as a truncated Fourier series. The optimum values of this series coefficient are obtained by an optimization process carried out using some built-in MATLAB functions. The width of the structures is deduced from the characteristic impedance by a standard method. All suggested microwave circuits are simulated using two trusted software packages. These are high frequency structure simulators (HFSS), and computer simulation technology (CST). The results of the two software packages are compared and shown to be in agreement.

Keywords— Impedance matching, Microstrip transformers, Nonuniform transmission lines.

I. INTRODUCTION

Transmission lines are the most important components used in microwave circuits because they are primarily responsible for power transmission between various ports. Power is one of the most critical issues in microwave systems. The reflection of power must be reduced as much as possible; and this goal is investigated by applying impedance matching. In order to satisfy this, several methods are employed such as quarter wave transformers, binomial transformers, Chebyshev transformers, and tapered transmission lines [1]. The major factors used to specify the appropriate method are complexity, bandwidth, and adjustability [1].

To keep pace with the rapid development of smart devices, combined with reducing their size, microwave systems are required to have smaller sizes. To accomplish this, microwave circuit components, as a transmission line, will be reduced. The compactness of the transmission line can be employed by using nonuniform transmission lines.

Nonuniform microstrip transmission lines (NTLs) are used for impedance matching in [2]. The strip width or the characteristic impedance of the microstrip (NTL) is expanded by a truncated Fourier series; and then by using a certain technique, the optimal values of the coefficients of the series are obtained. In [3], the author used multi-section transformers with different length for each section to match two complex loads. The lengths of sections were found also by an optimization process to satisfy the minimum value of a reflection coefficient in the desired frequency band. In [4], the authors used the Wentzel-Kramers-Brillouin approximation to achieve a direct synthesis of impedance matching over the passband region with nonuniform transmission lines. In [5], the authors used nonuniform microstrip transmission lines as patch antenna feeders which satisfy ultra-wide band matching of the microstrip rectangular patch antennas. In [6], the exponential tapered microstrip line was used to satisfy impedance matching. The optimum length of the tapered line was found by a particle swarm optimization (PSO) algorithm.

Corresponding author's e-mail: alazam_alaa@yahoo.com

In this paper, the same method used in [2] is followed. The aim is to compact quarter wave transformers, binomial transformers, Chebyshev transformers, and tapered lines. Uniform and nonuniform circuits are simulated using HFSS and CST software packages. These are high-performance full-wave electromagnetic (EM) field simulators for modeling devices of various topologies. HFSS uses a numerical technique called the Finite Element Method (FEM) which subdivides the structure into many smaller subsections called finite elements. A solution is found for the fields within the finite elements; and these fields are interrelated so that Maxwell's equations are satisfied across inter-element boundaries. CST uses Finite Integration Technique (FIT). Ansoft HFSS and CST have a much better interface which enables the user to include very fine details in the geometry of the simulated structure.

II. ANALYSIS OF NONUNIFORM TRANSMISSION LINE

In this section, the concept of nonuniform transmission line is presented. Nonuniform transmission line analysis was explained in [2], [7]. The main difference between uniform and nonuniform microstrip transmission lines is the dependence of the characteristic impedance on position $Z(z)$. Fig. 1 shows the uniform and the nonuniform transmission line; nonuniform microstrip characteristic impedance depends on the position, which makes the width, W, of the microstrip vary with position z. The compactness of length is investigated when $d < d_0$.

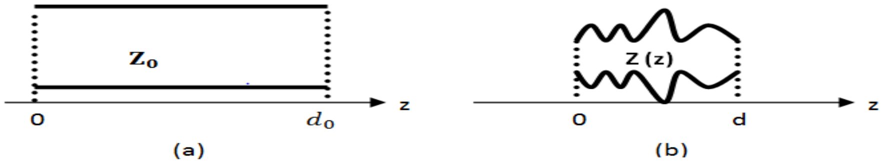


Fig. 1. a) Uniform transmission line, b) nonuniform transmission line

To get the nonuniform structure, the normalized characteristic impedance ($\bar{Z}(z) = Z(z)/Z_0$) can be presented as truncated Fourier series like in [2]:

$$ln(\bar{Z}(z)) = \sum_{i=0}^{N} C_i \, cos(2\pi nz/d) \tag{1}$$

where Z_0 is the characteristic impedance of the uniform transmission line, which is the counterpart of the nonuniform transmission line.

To facilitate dealing with nonuniform transmission line, the length is subdivided into many uniform short sections each of length Δz. Assuming that the number of subsections is k, the length is found to be as follows [2]:

$$\Delta z = \frac{d}{k} << \lambda_{min}, \text{ where } \lambda_{min} = \frac{c}{f_{max}\sqrt{\varepsilon_{eff}}} \tag{2}$$

where c is the speed of the light in the free space; d is the total length of the nonuniform transmission line (NTL); f_{max} is the maximum frequency of the analysis; and ε_{eff} is the effective relative electric permittivity of the k^{th} section. Then the well-known *ABCD* parameters of the total length (d) are found by multiplying the parameters of each uniform section as follows [2]:

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \prod_{n=1}^{k} \begin{bmatrix} A_n & B_n \\ C_n & D_n \end{bmatrix} \tag{3}$$

$$A_n = D_n = cos(\Delta\theta)$$

$$B_n = jZ\big((n-0.5)\Delta z\big)\,sin(\Delta\theta)$$

$$C_n = jZ^{-1}\big((n-0.5)\Delta z\big)\,sin(\Delta\theta)$$

$$\Delta\theta = \frac{2\pi}{\lambda}\,\Delta z$$

where Z is the characteristic impedance of the uniform short section.

Since the aim of the design is to match the impedance, the magnitude of the reflection coefficient $|\Gamma_{in}|$ is imposed to be zero or as small as possible. The total *ABCD* parameters are used to obtain Γ_{in} as follows [2]:

$$\Gamma_{in} = \frac{Z_{in}-Z_s}{Z_{in}+Z_s} \tag{4}$$

where Z_s is the source impedance; and Z_{in} depends on the total *ABCD* parameters which are presented by Z based on the $C_n's$ as shown in [2]:

$$Z_{in} = \frac{\mathrm{A\,Z_L+B}}{\mathrm{C\,Z_L+D}} \tag{5}$$

The optimum values of the coefficients $C_n's$ of the series that guarantee the aim of the design are obtained through an optimization approach which is performed using a built in MATLAB function "fmincon.m". Some constraints must be considered when solving the main function [2]. These can be summarized by:

$$\bar{Z}min \leq \bar{Z}(z) \leq \bar{Z}max \tag{6}$$

$$\bar{Z}(0) = \bar{Z}(d) = 1 \tag{7}$$

III. EXAMPLES OF UTL AND NUTL IMPEDANCE MATCHING COMPONENTS

In this section, quarter wave transformer, binomial transformer, Chebyshev transformer, and tapered line are designed and replaced by a compact nonuniform transmission line.

All designs are used to match a 100 Ω load to a 50 Ω line at 2.4 GHz using FR4 substrate with relative dielectric constant ε_r=4.6, height h=1.6 mm.

A. Design of Compact Quarter Wave Transformer Using Nonuniform Transmission Line

Quarter wave transformer is used to match two real impedances at a certain frequency. A quarter wave-transformer whose characteristic impedance is $Z_C = \sqrt{(100)(50)} = 70.71\,\Omega$, has a length $\ell = (\lambda/4)$=17.22 mm. Equation (5) is optimized subject to the minimum reflection coefficient objective function to find the Fourier coefficients $\{C_i\}$. These are shown in Table 1, where a length reduction of 34% is achieved. The compact quarter wave transformer is shown in Fig. 2. It is clear that the change of the width is very low in the middle of the designed microstrip. The simulated S-parameters for the quarter wave transformer and the compacted quarter wave transformer using HFSS and CST software are shown in Fig. 3. The figures show that the performance of the uniform structure is better than the nonuniform structure since its reflection coefficient is lower than the other. Yet, it can be seen that the input and output matching of the nonuniform structure is very good at the desired frequency (2.4 GHz). Taking the obtained reduction into account, it is good to use the nonuniform transformer.

TABLE 1
OPTIMIZED FOURIER COEFFICIENTS AND NORMALIZED CHARACTERISTIC IMPEDANCE FOR COMPACTED QUARTER WAVE TRANSFORMER

C_0	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}
-0.0959	-0.8276	0.0443	0.3988	0.1856	-0.0073	0.0369	0.1094	0.0860	0.0324	0.0375
$0.36 \leq \bar{Z} \leq 1.832$					$\lvert\Gamma\rvert$ = 0.0795 (used to investigate a good design)					

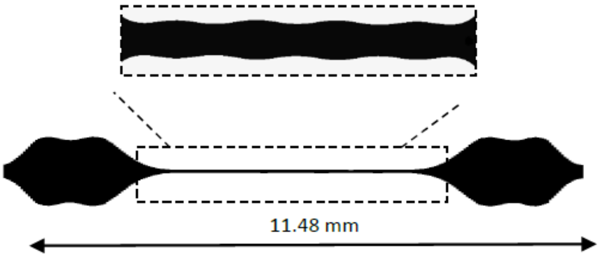


Fig. 2. Compact quarter wave transformer

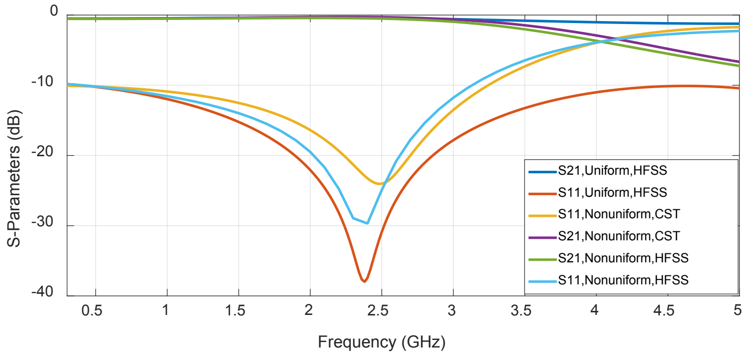


Fig. 3. Simulated S-parameters of quarter wave transformer (uniform) using HFSS and compacted quarter wave transformer (nonuniform) using HFSS and CST

B. Design of Compact Two-section Binomial Transformer Using Nonuniform Transmission Line

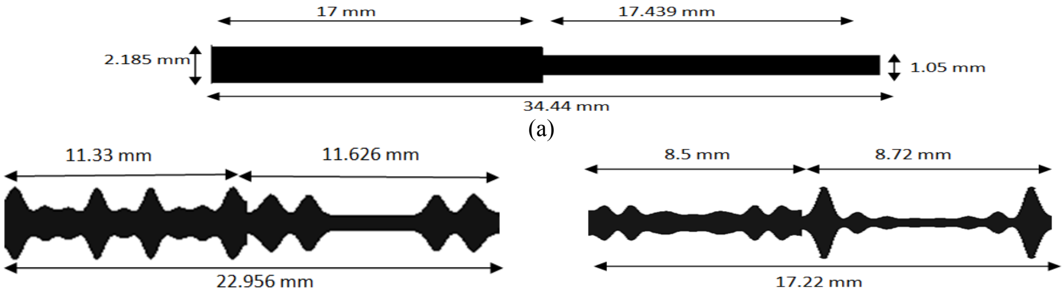
Binomial transformer is used to satisfy matching impedance in a wider range of frequency. By increasing the number of sections, the band of matching is increased. The characteristic impedance of the first section is Z_1=59.46 Ω; and for the second is Z_2=84.09 Ω. The $\lambda/4$ lengths of the first and second sections are 17 mm, and 17.439 mm, respectively. These are shown in Fig. 4a. Each section is compacted by 34%, and 50% at a single frequency $f_c =$ 2.4 GHz. The optimization process is applied for each section; and the $\{C_i\}$ coefficients are obtained. These are given in Tables 2 and 3. The resulted structures after combining the compacted sections are shown in Fig. 4b and 4c. Fig. 5 shows the simulated S-parameters of the two-section binomial transformer. The simulated results show that a good matching is obtained in all structures. The aim of using multisection is to increase the bandwidth, but the desired range must get good transmission coefficients with a good forward power. Fig. 5b shows the transmission coefficients of all transformers. It is clear that the bandwidth of the nonuniform transformer is better than that of the uniform transformer since it is good to get transmission coefficients greater than -1 dB. Therefore, using a nonuniform structure with 50% reduction is recommended to be used.

TABLE 2
OPTIMIZED FOURIER COEFFICIENTS AND NORMALIZED CHARACTERISTIC IMPEDANCE FOR 34% COMPACT TWO-SECTION BINOMIAL TRANSFORMER

C_0	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}
0.0737	-0.0640	-0.1219	-0.1169	0.0669	-0.1014	0.0842	0.0622	0.0087	0.1283	-0.0199
0.427≤ $\bar{Z}$ ≤2.178				Z=59.46 Ω		|Γ| = 0.1273 (used to investigate a good design)				
C_0	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}
-0.1108	-0.2202	0.1133	0.0422	-0.0498	0.1041	0.1721	0.0319	-0.0582	-0.0268	0.0022
0.303 ≤ $\bar{Z}$ ≤1.54				Z=84.09 Ω		|Γ| = 0.1214 (used to investigate a good design)				

TABLE 3
OPTIMIZED FOURIER COEFFICIENTS AND NORMALIZED CHARACTERISTIC IMPEDANCE FOR 50% COMPACT TWO-SECTION BINOMIAL TRANSFORMER

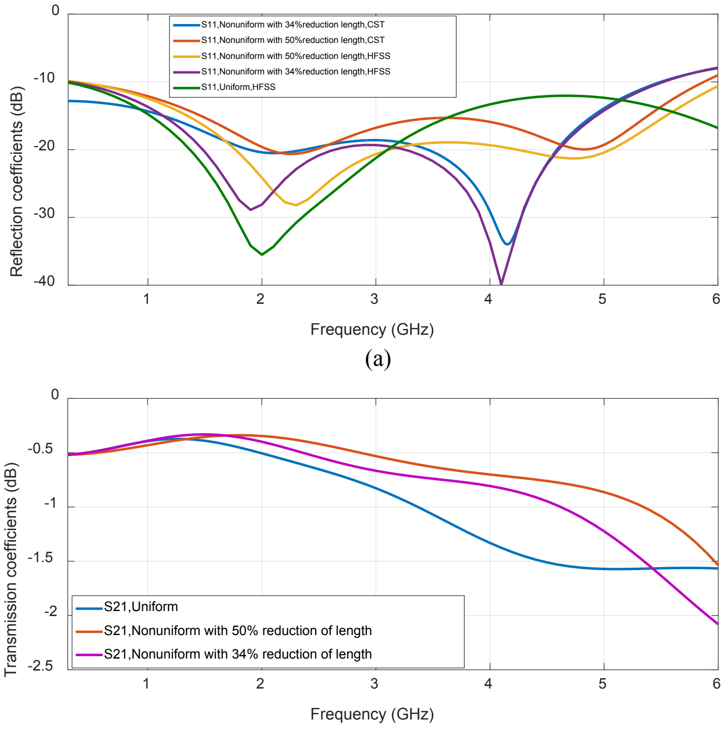
C_0	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}
0.0800	-0.1041	0.0096	-0.0119	0.0086	-0.0373	0.0625	0.1077	-0.0098	-0.0552	-0.0503
0.427≤ $\bar{Z}$ ≤2.178				Z=59.46 Ω		|Γ| = 0.1980 (used to investigate a good design)				
C_0	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}
-0.0950	-0.3362	-0.0790	0.0205	0.1054	0.1546	0.1806	0.1714	0.0164	-0.1104	-0.0282
0.303 ≤ $\bar{Z}$ ≤1.54				Z=84.09 Ω		|Γ| = 0.1726 (used to investigate a good design)				



(a)

(b) (c)

Fig. 4. Two-section binomial transformer: a) uniform sections, b) nonuniform sections with 34% length reduction, c) nonuniform sections with 50% length reduction



(a)

(b)

Fig. 5. Simulated S-parameters of two-section binomial transformer: a) reflection coefficients of uniform sections, nonuniform sections with 34% length reduction, and nonuniform sections with 50% length reduction, b) transmission coefficients of the three transformers using HFSS

C. Design of Compact Two-section Chebyshev Transformer Using Nonuniform Transmission Line

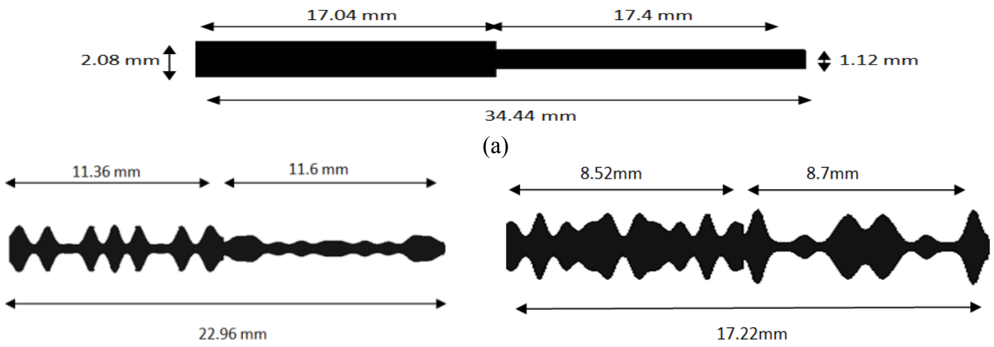
Chebyshev transformer is used to satisfy matching impedance in a wider range of frequency conditions than the binomial transformer in spite of using the same number of sections. The characteristic impedance of the first section is Z_1=61 Ω; and for the second is Z_2=82 Ω. The $\lambda/4$ lengths of the first and second sections are 17.04 mm, and 17.4 mm, respectively, as shown in Fig. 6a. Each section is compacted by 34% and 50% at a single frequency f_c = 2.4 GHz**.** The $\{C_i\}$ coefficients are found in Tables 4 and 5. The designed structures are shown in Fig. 6b and 6c. The simulated S-Parameters are shown in Fig. 7a. It is clear that an acceptable matching is obtained in the desired band. Fig. 7b shows that transmission coefficients of nonuniform structures are better than those of uniform structures. This means the bandwidth obtained from nonuniform structures is greater than that of the uniform structures.

TABLE 4
OPTIMIZED FOURIER COEFFICIENTS AND NORMALIZED CHARACTERISTIC IMPEDANCE FOR 34% COMPACT TWO-SECTION CHEBYSHEV TRANSFORMER

C_0	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}
0.0408	-0.0778	-0.1818	0.0470	0.0169	-0.1941	-0.0341	0.2266	0.0410	0.2268	-0.1113
0.42≤ $\bar{Z}$ ≤2.123				Z=61 Ω		|Γ| = 0.1133 (used to investigate a good design)				
C_0	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}
-0.0801	-0.1297	-0.0942	0.0480	0.0806	0.0983	0.0136	0.0332	-0.0495	0.0050	0.0748
0.31 ≤ $\bar{Z}$ ≤1.57				Z=82 Ω		|Γ| = 0.1646 (used to investigate a good design)				

TABLE 5
OPTIMIZED FOURIER COEFFICIENTS AND NORMALIZED CHARACTERISTIC IMPEDANCE FOR 50% COMPACT TWO-SECTION CHEBYSHEV TRANSFORMER

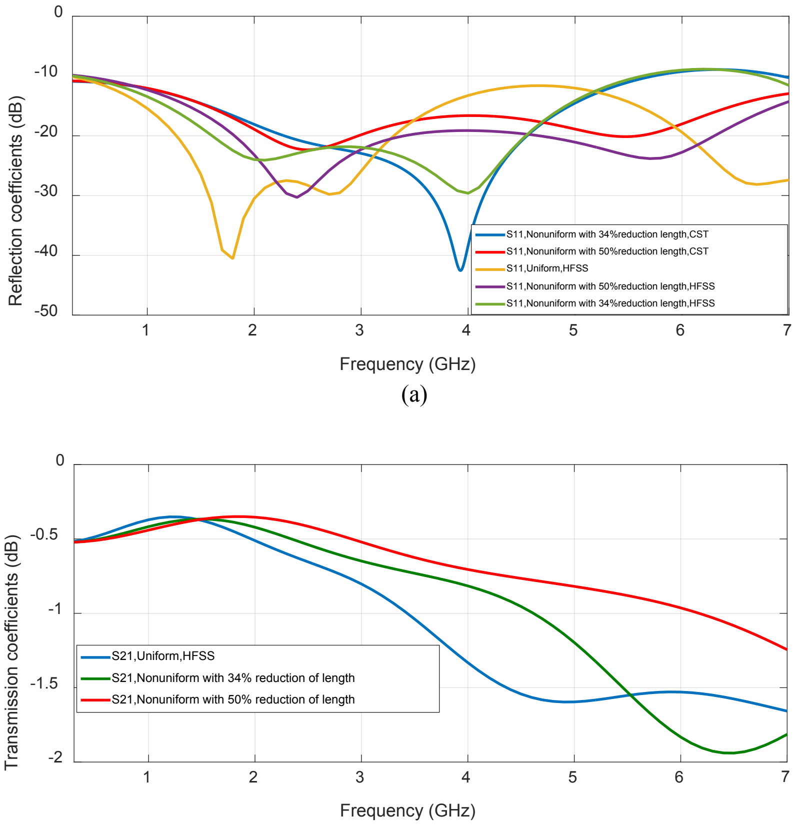
C_0	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}
0.0543	0.0522	-0.0372	-0.0359	0.0490	-0.0886	-0.0003	-0.1561	-0.0161	0.0403	0.1383
0.42≤ $\bar{Z}$ ≤2.123				Z=61 Ω		|Γ| = 0.1725 (used to investigate a good design)				
C_0	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}
-0.0441	0.0767	-0.3469	-0.0636	-0.0441	-0.0552	0.2403	0.0637	0.0455	0.0617	0.0661
0.31 ≤ $\bar{Z}$ ≤1.57				Z=82 Ω		|Γ| = 0.1610 (used to investigate a good design)				



(a)

(b) (c)

Fig. 6. Two-section Chebyshev transformer: a) uniform sections, b) nonuniform sections with 34% length reduction, c) nonuniform sections with 50% length reduction



(a)

(b)

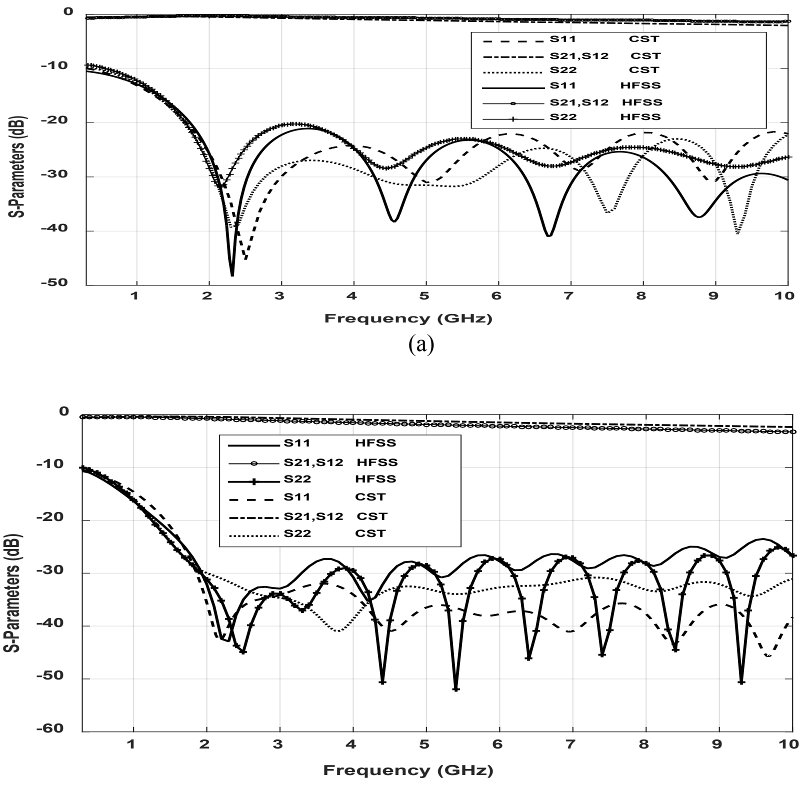
Fig. 7. Simulated S-parameters of two-section Chebyshev transformer: a) reflection coefficients of uniform sections, nonuniform sections with 34% length reduction, and nonuniform sections with 50% length reduction, b) transmission coefficients of the three transformers using HFSS

D. *Design of Compact Multisection Transformer Using Tapered Transmission Line*

Using continuous-taper instead of discrete sections satisfies a wider range of bandwidths. The most popular types of taper are exponential and triangular tapers whose characteristic impedance and width depend on position $Z(z)$. The small reflection can be obtained when the exponential line length is greater than $\lambda/2$; and the triangle length is λ [8]. The designed structures are built by choosing 2.4 GHz to find their lengths as shown in the exponential tapered line in Fig. 8a, and triangular tapered line in Fig. 8b. The simulated S-parameters are shown in Fig. 9a and 9b. Good matching is obtained over a wide band range, i.e., from 0.3 GHz-10 GHz.

(a) (b)

Fig. 8. Tapered transmission line: a) exponential, b) triangular



(a)

(b)

Fig. 9. Simulated S-parameters of tapered transmission line: a) exponential, b) triangular

Quarter wave transformer with characteristic impedance $Z_c = 70.71\ \Omega$ and length 11.5 mm as shown in Fig. 10 is used instead of multisection transformer to cover the same range of frequencies by optimization in the range (0.3 GHz-4.8 GHz) instead at single frequency. The C_i values are in Table 6. Fig. 11 shows the simulated S-parameters of the transmission line. Good matching is obtained at a wide range compared to the result obtained in Fig. 3. Also, a reduction in size is achieved. It is to be noted here that the match obtained here is not better than taper lines, but the nonuniform is recommended here since its length is smaller than others (it is 66% less than exponential and 83% less than triangular taper length); and transmission coefficients are better than the taper lines in order to cover the widest range as shown in Fig. 12.

TABLE 6

OPTIMIZED FOURIER COEFFICIENTS AND NORMALIZED CHARACTERISTIC IMPEDANCE FOR COMPACTED QUARTER WAVE TRANSFORMER

C_0	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}
-0.0466	0.0335	0.0534	0.0127	0.0541	0.0278	-0.0616	0.0050	0.0861	0.0358	-0.0279
0.31≤ $\bar{Z}$ ≤1.83										

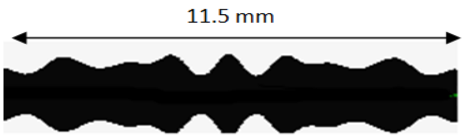


Fig. 10. Compacted quarter wave transformer

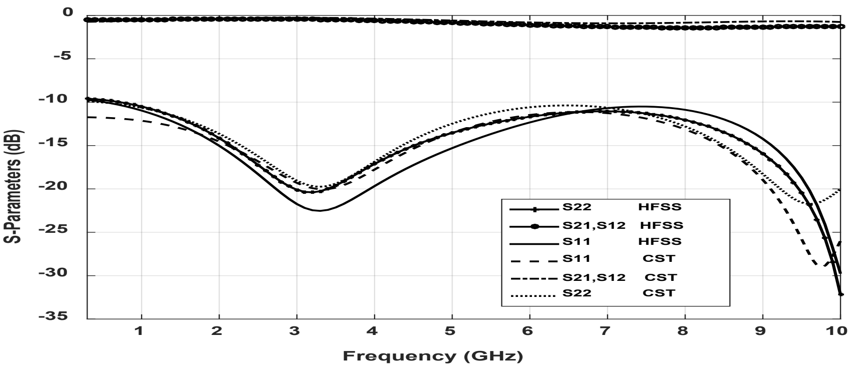


Fig. 11. Simulated S-parameters of compacted quarter wave transformer

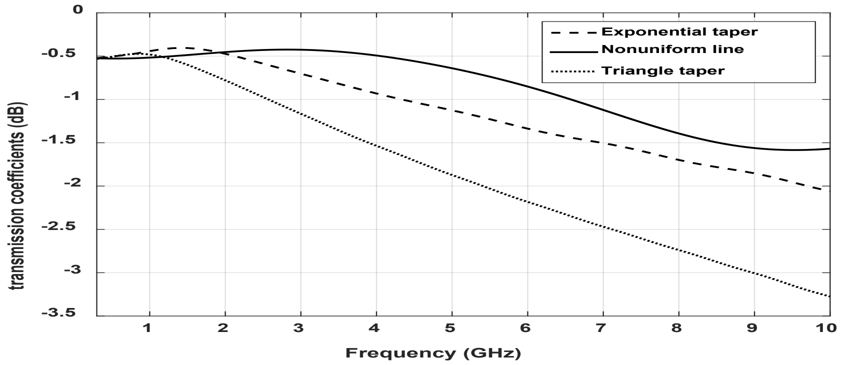


Fig. 12. Simulated transmission coefficients of exponential, triangular, and nonuniform line

Table 7, lists a comparison between the proposed designs; the bandwidth depends on the simulated transmission coefficients that need to be greater than -1 dB. Simulated reflection coefficients must be less than -10 dB. It is clear that the bandwidth of the compacted transformers is greater than other. This is considered another advantage added to the length reduction.

TABLE 7

COMPARISON BETWEEN THE PROPOSED DESIGNS

Proposed Design	Total Length, mm	Bandwidth, GHz
Binomial transformer	34.44	3.4
Compacted Binomial transformer with 34% length reduction	22.956	4.6
Compacted Binomial transformer with 50% length reduction	17.22	5.35
Chebyshev transformer	34.44	3.5
Compacted Chebyshev transformer with 34% length reduction.	22.96	4.62
Compacted Chebyshev transformer with 50% length reduction	17.22	6.2
Exponential line	34.35	4.4
Triangular line	68.68	2.7
Compacted taper line	11.5	5.7

IV. CONCLUSION

Impedance matching components are designed using the uniform microstrip transmission line, which can be realized via various configurations. The paper considered quarter wave transformers to match the source impedance, real load, wideband multisection transformers of Binomial and Chebyshev, and tapered lines. These components are compacted by letting the line to be nonuniform. Length reduction is achieved without changing the desired operating frequency band. Simulated responses, using two well-known software packages, are given for the uniform and compacted components. An agreement between HFSS and CST results is achieved. The given results are awaiting verifications by producing a prototype.

REFERENCES

[1] D. Pozar, *Microwave Engineering*, John Wiley and Sons, 2012.

[2] M. Khalaj-Amirhosseini, "Wideband or multiband complex impedance matching using microstrip nonuniform transmission lines," *Progress in Electromagnetic Research*, vol. 66, pp. 15-25, 2006.

[3] M. Khalaj-Amirhosseini, "Wideband complex impedance matching using unequal-length multi-section transformers," *Proceedings of International Symposium on Antennas and Propagation*, pp. 999-1002, 2007.

[4] Y. Hsu and E. Kuester, "Direct synthesis of passband impedance matching with nonuniform transmission lines," *IEEE Transactions on Microwave Theory and Techniques*, vol. 58, no. 4, pp. 1012-1021, 2010.

[5] G. Ngendakumana and N. Elouazzani, "Ultra wide band matching of the rectangular microstrip patch antennas (RMPA) using microstrip nonuniform transmission lines (MNUTL)," *Computer Science Issues*, vol. 9, no. 3, pp. 355-361, 2012.

[6] M. Belen, S. Demirel, F. GÄunes and A. Keskin, "Design optimization of the xponentially tapered microstrip impedance matching sections using a cost effective 3-D-SONNET-based SVRM with the particle swarm intelligence," *Proceedings of Progress in Electromagnetic Research Symposium*, pp. 1490-1494, 2013.

[7] M. Khalaj-Amirhosseini, "Nonuniform transmission lines as compact uniform transmission lines," *Progress in Electromagnetic Research C*, vol. 4, pp. 205-211, 2008.

[8] R. Collin, *Foundations for Microwave Engineering*, John Wiley and Sons, 2000.