Ultra-High Transforming Ratio Coupled Line Impedance Transformer With Bandpass Response

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***Abstract*—An impedance transformer (IT) with a ultra-high impedance transforming ratio (UHITR) is presented in this letter. The UHITR is obtained by controlling coupling coefficients of cascaded open-circuited coupled lines. Two transmission poles have appeared in the passband for an under-matched region. For the validation, the IT with impedance transforming ratio of 10 was designed at a center frequency (f_0) of 2.6 GHz. From the experiment, insertion and return losses at f_0 were determined as 0.55 dB and 21.47 dB, respectively. Within the operating band from 2.515 to 2.73 GHz, the insertion and return losses were better than 0.8 dB and 18 dB, respectively. The out-of-band suppression characteristics are higher than 20 dB from dc to 1.92 GHz and better than 18 dB from 3.28 to 7.2 GHz.**

***Index Terms*—Coupled line, impedance transformer, transmission poles, ultra-high impedance transforming ratio.**

I. Introduction

IMPEDANCE transformers (IT) have been widely used in various applications such as power dividers, antenna feeding lines, and power amplifiers [1]. However, ultra-high impedance transforming ratio (UHITR) ITs are rarely presented in previous works due to the realization of difficulty in microstrip line. A $\lambda/4$ transmission line (TL) is well-known as an IT which has limitations such as narrow bandwidth, poor out-of-band suppression, and difficulty in realization for UHITR. To overcome limitations, various coupled line ITs have been described [2]–[5]. In [2], a coupled three-line was used to get a wide passband response for an impedance transforming ratio (r) of 3.4. However, the out-of-band suppression is poor with restricted in r. In [3], an open-circuited coupled line IT with $r = 2$ was presented. Similarly, the coupled line IT with a shunt TL for $r = 2$ was investigated and provided good out-of-band suppression [4]. An unequal terminated coupled line bandpass filter with $r = 1.5$ was presented in [5] using optimization technique.

In this letter, UHITR IT with a bandpass response is presented by cascading two open-circuited coupled lines. The circuit elements of the proposed IT can be found easily by using analytical design equations. The proposed network can provide two transmission poles in the passband as well as wide out-of-band suppression characteristics and can be fabricated without any difficulty in microstrip technology.

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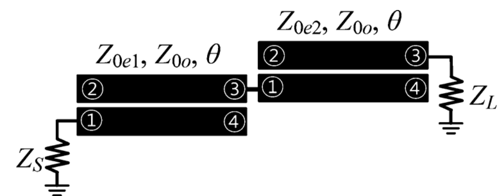

Fig. 1. Proposed circuit for ultra-high impedance transforming ratios.

II. Design Equations

Fig. 1 shows the proposed structure of the UHITR IT. The proposed IT consists of two sections of open-circuited coupled lines with even-mode impedances (Z_{0e1}, Z_{0e2}) and odd-mode impedance (Z_{0o}), respectively. The Z_{0o} of both coupled lines is assumed to be the same for convenience and simplicity in the analysis. The S-parameters of the proposed circuit can be found as (1) from the overall ABCD-parameters of cascaded coupled lines [4]–[6]

$$S_{11t} = \frac{AZ_L + B - CrZ_L^2 - DrZ_L}{AZ_L + B + CrZ_L^2 + DrZ_L} \tag{1a}$$

$$S_{21t} = \frac{2Z_L\sqrt{r}}{AZ_L + B + CrZ_L^2 + DrZ_L} \tag{1b}$$

where

$$A = \left[(Z_{p1}+Z_{p2})Z_{p1}\cos^2\theta - Z_{m1}^2\right]/(Z_{m1}Z_{m2}) \tag{2a}$$

$$B = j\cot\theta\left[\frac{Z_{p1}Z_{m2}^2 + Z_{m1}^2Z_{p2} - (Z_{p1}+Z_{p2})\,Z_{p1}Z_{p2}\cos^2\theta}{2Z_{m1}Z_{m2}}\right] \tag{2b}$$

$$C = j2\sin\theta\cos\theta(Z_{p1}+Z_{p2})/(Z_{m1}Z_{m2}) \tag{2c}$$

$$D = \left[(Z_{p1}+Z_{p2})Z_{p2}\cos^2\theta - Z_{m2}^2\right]/(Z_{m1}Z_{m2}) \tag{2d}$$

$$Z_{m1} = Z_{0e1} - Z_{0o}, \quad Z_{m2} = Z_{0e2} - Z_{0o} \tag{2e}$$

$$Z_{p1} = Z_{0e1} + Z_{0o}, \quad Z_{p2} = Z_{0e2} + Z_{0o} \tag{2f}$$

$$r = Z_S/Z_L. \tag{2g}$$

And the electrical length (θ) is $\pi/2$ at f_0.

At f_0, S_{11t} of the proposed circuit is reduced to

$$S_{11t}|_{f=f_0} = \frac{Z_{m1}^2 - rZ_{m2}^2}{Z_{m1}^2 + rZ_{m2}^2}. \tag{3}$$

In (3), S_{11t} depends on even- and odd-mode impedances of coupled lines. From (3), three different matched regions are categorized [4], depending on the values of Z_{m1} and Z_{m2}, as

$$Z_{m1}^2 > rZ_{m2}^2 : \text{ over-matched region} \tag{4a}$$

$$Z_{m1}^2 < rZ_{m2}^2 : \text{ under-matched region} \tag{4b}$$
$$Z_{m1}^2 = rZ_{m2}^2 : \text{ perfectly matched region.} \tag{4c}$$

For the over-matched region with the specific S_{11t}, the value of Z_{0e2} can be calculated as (5) using (3)

$$Z_{0e2} = Z_{0e1}M + Z_{0o}(1-M) \tag{5}$$

where

$$M = \sqrt{1/r\left(1 - S_{11t}|_{f=f_0}\right) \Big/ \left(1 + S_{11t}|_{f=f_0}\right)}. \tag{6}$$

The value of Z_{0e1} can be derived as (7) using (1a), (4a), and (5) for the assumed Z_{0o} by designer

$$Z_{0e1}^3 X_{o1} + Z_{0e1}^2 X_{o2} + Z_{0e1} X_{o3} + X_{o4} = 0 \tag{7}$$

where

$$X_{o1} = M(1+M) \tag{8a}$$
$$X_{o2} = Z_{0o}(2 - M^2 - 3M) \tag{8b}$$
$$X_{o3} = (3M - M^2 - 4)Z_{0o}^2 - 4rZ_L^2(M+1) \tag{8c}$$
$$X_{o4} = Z_{0o}^3(M^2 - M + 2) + 4rZ_L^2 Z_{0o}(M-3). \tag{8d}$$

The negative and minimum positive root of (7) are not realizable for coupled line application ($Z_{0e1} < Z_{0o}$). So the proper Z_{0e1} is the maximum real positive root of (7).

Similarly, for the under-matched region with the specific S_{11t}, the value of Z_{0e2} can be found as

$$Z_{0e2} = Z_{0e1}N + Z_{0o}(1-N) \tag{9}$$

where

$$N = \sqrt{1/r(1 + S_{11t}|_{f=f_0})/(1 - S_{11t}|_{f=f_0})}. \tag{10}$$

From (1a), (4b), and (9), the value of Z_{0e1} for the under-matched region is derived as (11)

$$Z_{0e1}^3 Y_{u1} + Z_{0e1}^2 Y_{u2} + Z_{0e1} Y_{u3} + Y_{u4} = 0 \tag{11}$$

where

$$Y_{u1} = N(1+N) \tag{12a}$$
$$Y_{u2} = Z_{0o}(2 - N^2 - 3N) \tag{12b}$$
$$Y_{u3} = (3N - N^2 - 4)Z_{0o}^2 - 4rZ_L^2(N+1) \tag{12c}$$
$$Y_{u4} = Z_{0o}^3(N^2 - N + 2) + 4rZ_L^2 Z_{0o}(N-3). \tag{12d}$$

Similar to over-matched region, the proper Z_{0e1} among the three Z_{0e1} values is the maximum real positive root of (11).

For the perfectly matched region, S_{11t} becomes zero, such that the value of Z_{0e2} can be found as

$$Z_{0e2} = Z_{0e1}/\sqrt{r} + Z_{0o}(1 - 1/\sqrt{r}). \tag{13}$$

From (1a), (4c), and (13), the value of Z_{0e1} for the perfectly matched region can be derived as

$$Z_{0e1}^3 W_{p1} + Z_{0e1}^2 W_{p2} + Z_{0e1} W_{p3} + W_{p4} = 0 \tag{14}$$

where

$$W_{p1} = 1/r + 1/\sqrt{r} \tag{15a}$$
$$W_{p2} = Z_{0o}(2 - 1/r - 3/\sqrt{r}) \tag{15b}$$
$$W_{p3} = \left(3/\sqrt{r} - 1/r - 4\right) Z_{0o}^2 - 4rZ_L^2(1/\sqrt{r} + 1) \tag{15c}$$
$$W_{p4} = Z_{0o}^3(1/r - 1/\sqrt{r} + 2) + 4rZ_L^2 Z_{0o}(1/\sqrt{r} - 3). \tag{15d}$$

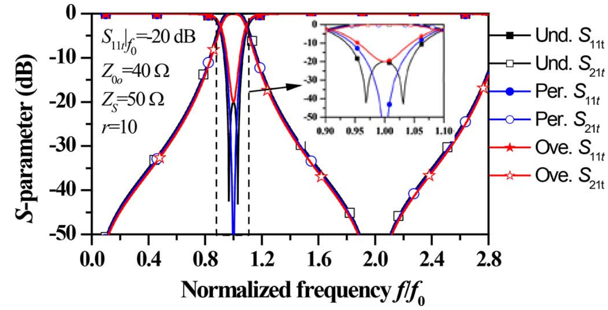

Fig. 2. Frequency responses of transformer for three different matched regions.

TABLE I
CALCULATED VALUES OF IMPEDANCE TRANSFORMER

Match regions	Z_{0o}=40 Ω $S_{11t}\|_{f=f_0}$=-20 dB, Z_S=50 Ω, r=10					
	Z_{0e1} (Ω)	Z_{0e2} (Ω)	C_1 (dB)	C_2 (dB)	f_{p1}/f_0	f_{p2}/f_0
Under	84.57	55.58	-8.9	-15.7	0.9687	1.0313
Over	86.02	53.16	-8.7	-17		
Perfect	85.34	54.34	-8.8	-16.4		

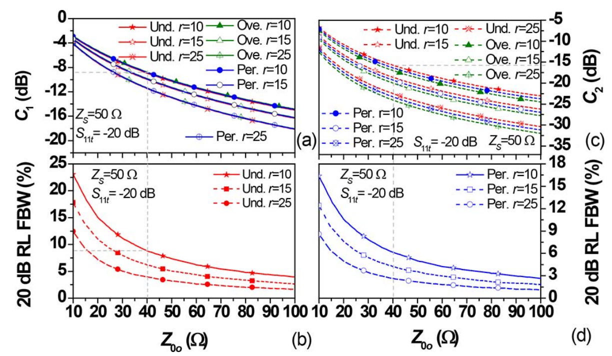

Fig. 3. Design graph according to Z_{0o} and different r: (a) C_1, (b) 20 dB return loss (RL) FBW of under-matched region, (c) C_2, and (d) 20 dB RL FBW of perfectly matched region.

Also, the proper Z_{0e1} is the maximum real positive root of (14).

The coupling coefficients (C_i) of coupled lines are shown as

$$C_i = (Z_{0ei} - Z_{0o})/(Z_{0ei} + Z_{0o}) \tag{16}$$

where i is 1 and 2 for the coupled line 1 and 2, respectively.

To illustrate the design equations (5)–(16) of the UHITR IT, the required Z_{0e1} and Z_{0e2} are calculated by specifying $S_{11t}|_{f0} = -20$ dB, $Z_{0o} = 40\ \Omega$, $r = 10$, and $Z_S = 50\ \Omega$ at f_0. The calculated values are given in Table I. Using the calculated values, the frequency responses are plotted in Fig. 2 for different matched regions. As seen in Fig. 2, a bandpass filtering response is obtained. The magnitude of return loss ($S_{11t}|_{f0}$) is exactly 20 dB at the f_0 in case of under- and over-matched regions. While two transmission poles are observed in the passband for the under-matched region, only one transmission pole at f_0 is observed in the cases of over- and perfectly matched regions. Thus, the under-matched region is preferable for its wide return loss bandwidth characteristic.

The normalized transmission pole frequencies observed in the under-matched region can be found as (17) using (1a)

$$f_{p1,p2}/f_0 = 1 \mp \left[1 - \frac{2}{\pi}\cos^{-1}\sqrt{\frac{Z_{m1}^2 - rZ_{m2}^2}{(Z_{p2}+Z_{p1})(Z_{p1}-rZ_{p2})}}\right] \tag{17}$$

where f_{p1} and f_{p2} are the lower and upper transmission pole frequencies, respectively.

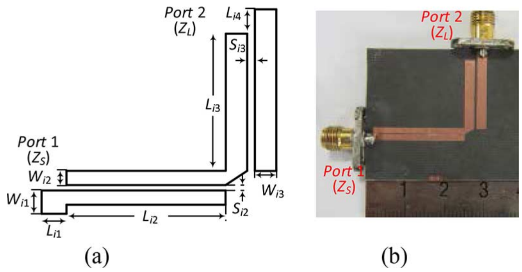

Fig. 4. (a) EM simulation layout and (b) photograph of fabricated PCB. ($W_{i1} = 2.4, L_{i1} = 2, W_{i2} = 1.35, L_{i2} = 22.7, S_{i2} = 0.3, W_{i3} = 2.4, L_{i3} = 17.2, S_{i3} = 0.65$, and $L_{i4} = 3$) (unit: mm).

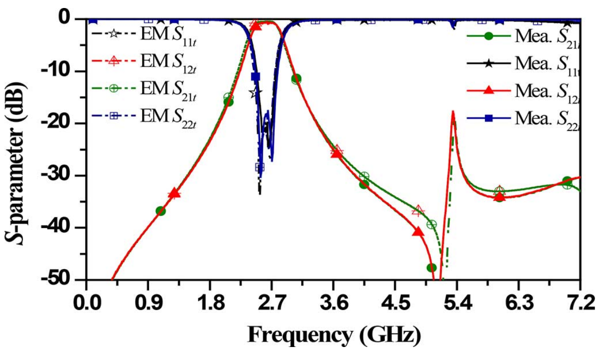

Fig. 5. EM simulation and measurement results.

TABLE II
PERFORMANCE COMPARISON WITH PREVIOUS WORKS

Ref.	f_0 (GHz)	FBW (%)	Impedance ratio (r)	>18 dB Out-of-band suppression	PCB Technology
[2]	1.5	*85	3.4	NA	Strip Line
[3]	2	≈*7	2	NA	Microstrip Line
[4]	2.6	*35	2	DC-1.42 / 3.8-6.65 GHz	Microstrip Line
[5]	3	**20	1.5	*** 2.4-2.56 / 3.5-4.32 GHz	Microstrip Line
This work	**2.6**	**8.27** (-18 dB S_{11})	**10**	DC-2 / 3.28-7.2 GHz	**Microstrip Line**

*: -20 dB S_{11} FBW, **: -12 dB S_{11} FBW, ***: estimated from Fig. 5 of [5]

To illustrate the relation between 20 dB return loss (RL) fractional bandwidth (FBW) and C_i according to Z_{0o} with different r, the calculated values are plotted in Fig. 3 for all matched regions. As shown in Fig. 3(a)-(c), loose coupling coefficients are obtained with high Z_{0o}. However, a wide FBW can be obtained with low Z_{0o} which increase $C_{\rm i}$ as shown in Fig. 3(b)-(d). The 20 dB RL FBW of the under-matched region is wider than perfectly and over-matched regions. On the other hand, the FBWs of under-matched and perfectly matched regions are proportional to r. The 20 dB RL FBW of the over-matched region is only one point at f_0, which is not presented on the graph. Thus, the tradeoff between FBW and C_i should be considered.

The design procedure of IT is summarized as follows.

a) First, specify the Z_S, Z_L, Z_{0o}, f_0, and $|S_{11t}|$ at f_0 for all matched regions.
b) For the over-matched region, calculate Z_{0e1} using (6), (7), and (8). After obtaining Z_{0e1}, calculate Z_{0e2} using (5).
c) For the under-matched region, calculate Z_{0e1} using (10), (11), and (12). Then calculate Z_{0e2} using (9).
d) For the perfectly matched region, calculate Z_{0e1} using (14) and (15). Then Z_{0e2} is obtained by (13).
e) Finally, obtain the physical dimensions of coupled lines according to PCB substrate from the LineCalc of Advanced Design System (ADS) and optimize using EM simulator.

III. SIMULATION AND MEASUREMENT RESULTS

For verification, a 5-to-50 Ω ($r = 10, Z_S = 50\ \Omega$) UHITR IT was designed, simulated, and fabricated at $f_0 = 2.6$ GHz. The MATLAB tool was used to calculate the elements values. For this purpose, the values of S_{11t} and Z_{0o} are chosen as -20 dB and 40 Ω at f_0, respectively. In this design, the under-matched region was chosen. The calculated values are shown in Table I. The EM simulation was performed using Ansoft's HFSS v13.

The proposed circuit was fabricated on a substrate with $\varepsilon_r = 2.2$ and $h = 31$ mils. Fig. 4 shows the layout and a photograph of the fabricated UHITR IT. The overall circuit size of fabricated network is 30×25 mm^2. The ADS simulator and network analyzer were co-used to measure proposed UHITR IT. Fig. 5 shows the simulation and measurement results of the proposed circuit. The measured results showed good agreement with the simulation results. The measured S_{21t} and S_{11t} at $f_0 = 2.6$ GHz were -0.55 dB and -21.47 dB, respectively. The 18 dB return loss frequency band is from 2.515 to 2.73 GHz (FBW = 8.27%). The maximum S_{11} and S_{22} in frequency band are -19.92 dB and -18.18 dB, respectively. Two transmission poles are located at 2.54 GHz and 2.67 GHz. The bandpass characteristic is obtained with wide out-of-band suppression. However, a spurious response occurred at around $2f_0$ due to the different even- and odd-modes of the coupled lines on the microstrip line [7]. The out-of-band suppression characteristics are higher than 20 dB from dc to 1.92 GHz and better than 18 dB from 3.28 to 7.2 GHz. The performance comparisons are summarized in Table II. Although [5] provides wider FBW and bandpass response, however, r is small.

IV. CONCLUSION

An impedance transformer with UHITR is proposed, investigated, and fabricated in this letter. The UHITR is obtained by controlling coupling coefficients of coupled lines. The proposed circuit is fabricated without difficulty with microstrip line technology. By choosing the properly matched region of coupled lines, two transmission poles are obtained in the passband. A low insertion loss is obtained with high impedance transforming ratio and provide a bandpass response.

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