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High selectivity and wideband bandpass filtering impedance transformer

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Abstract

An impedance transformer (IT) with wideband and high selectivity is presented in this paper. Three transmission poles were obtained within the passband and provides a wide passband response. Moreover, there are two transmission zeros (TZs) close to the passband that were achieved by a shunt parallel coupled line and provide high selectivity. For validation of proposed circuit, the ITs were designed at a center frequency (f_0) of 3.5 GHz using an impedance-transforming ratio (r) of 5 and 10. For $r = 5$, $|S_{21}|$ and $|S_{11}|$ are 0.36 dB and 28 dB at f_0, respectively. Within the passband, $|S_{21}|$ and $|S_{11}|$ are better than 0.65 dB and 18 dB, respectively. The TZs at 2.65 GHz ($0.76f_0$) and $1.22f_0$, close to the passband, were measured with attenuation better than 37 dB. The out-of-band attenuations are higher than 20 dB from DC to 2.77 GHz of the lower stopband and from 4.16 GHz to 9.73 GHz of the higher stopband. For $r = 10$, $|S_{21}| = -1.4$ dB and $|S_{11}| = -23$ dB were measured at f_0. An 18 dB return loss was obtained from 3.415 GHz to 3.694 GHz (FBW = 7.96%).

KEYWORDS

Bandpass filtering, coupled line, impedance transformer, transmission poles

1 | INTRODUCTION

Wideband and high selectivity impedance transformers (ITs) have been widely researched for use in various applications such as antenna feeding lines[1] and power amplifiers.[2] There are many challenges to designing ITs that possess a wideband, high selectivity, and high impedance transforming ratio (r) simultaneously. In,[3] two parallel coupled line IT with bandpass response was designed with $r = 10$. Although the high r and filtering response were obtained, they only achieved a fractional bandwidth (FBW) of 8.27%. Similarly, a multilayer two cascade parallel coupled lines IT with FBW of 50% was presented in[4] with $r = 2$. On the other hand, the wideband ITs using quarter-wavelength ($\lambda/4$) parallel coupled line with air bridge connection stepped impedance transmission line (TL) and open/short-circuited TLs were designed in the microstrip line.[5-9] FBWs beyond 60% and 100% were obtained in these works with an r of only 2 as well as poor stopband characteristics. In,[10] a bandpass filtering IT using a $\lambda/4$ parallel coupled line with a shunt $\lambda/2$ TL was designed, this achieved $r = 5$. This IT provided a FBW of 13.5% with transmission zeros (TZs) at $0.5f_0$ and $1.5f_0$. In,[11] the SIR BPF with arbitrary real-to-real termination impedance was designed. The spurious frequency could be controlled by the changing stepped impedance ratios; however, the FBW was less than 10%.

In this paper, a high selectivity IT with a wideband, high r, and bandpass response is analyzed, designed, and tested. The proposed IT provides three transmission poles in the passband. Moreover, the TZs that close to the passband are controllable and provide high selectivity. The other 5 TZs that achieved in the stopband are provided a wide out-of-band suppression.

2 | ANALYSIS

Figure 1 shows the proposed structure of the high selectivity wideband IT. The proposed IT consists of two parallel coupled lines and an open stub TL. The parallel coupled line has odd- and even-mode impedances (Z_{0o} and Z_{0e}) and an electrical length of θ_1, it is terminated with an open stub TL that has a characteristic impedance of Z_1 and an electrical length of $2\theta_1$. The shunt open-circuited parallel coupled line with even- and odd-mode impedances (Z_{0es} and Z_{0os}) and an electrical length of θ_1 is connected at the output port to produce controllable transmission zeros. The S-parameters of the proposed circuit can be found as (1) from the overall $ABCD$-parameters of cascaded coupled lines.

$$S_{11}=\frac{ArZ_S+B-CrZ_S^2-DZ_S}{ArZ_S+B+CrZ_S^2+DZ_S}, \tag{1a}$$

$$S_{21}=\frac{2Z_S\sqrt{r}}{ArZ_S+B+CrZ_S^2+DZ_S}, \tag{1b}$$

where

$$A=A_c+B_cC_s, B=B_c, C=C_c+D_cC_s, D=D_c, \tag{2a}$$

$$A_c=x_1\cot\theta/x_2, \tag{2b}$$

$$B_c=j\left(Z_p\cot\theta x_1x_4+2{x_2}^2\right)/2x_2x_3, \tag{2c}$$

$$C_c=jx_3/x_2, \tag{2d}$$

$$C_s=j\frac{2Z_{ps}\cos\theta\sin\theta}{Z_{ps}^2\cos^2\theta-{Z_{ms}}^2}, \tag{2e}$$

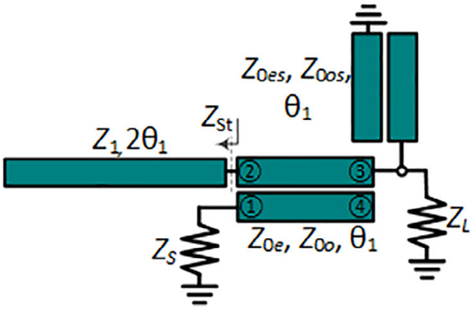

FIGURE 1 Proposed wideband and high selectivity impedance transformer

$$D_c=-Z_px_4/2x_2, \tag{2f}$$

$$x_1=2Z_{0ec}Z_{0oc}\cot\theta+Z_1Z_p\cot2\theta, \tag{2g}$$

$$x_2=Z_mZ_1\cot2\theta\csc\theta, \tag{2h}$$

$$x_3=2Z_1\cot2\theta+Z_p\cot\theta, \tag{2i}$$

$$x_4=Z_p-2Z_1\cot\theta\cot2\theta, \tag{2j}$$

$$Z_{mc,s}=Z_{0ec,s}-Z_{0oc,s}, \quad Z_{pc,s}=Z_{0ec,s}+Z_{0oc,s}, \tag{2k}$$

$$r=Z_L/Z_S, \tag{2l}$$

where c and s stand for the parallel coupled line and shunt coupled line, respectively. And Z_L must be high than Z_S.

From (1a), the Z_{0e} of the parallel coupled line can be derived as (3).

$$Z_{0e}=2Z_S\sqrt{r}+Z_{0o}. \tag{3}$$

The pair transmission zeros (TZs) can be produced by the shunt parallel coupled line and their frequencies can be derived as (4).[12]

$$f_{Zcs}=f_0(m+a), m:1,3,5,\cdots \tag{4}$$

where

$$a=\pm\frac{2}{\pi}\sin^{-1}\left(\frac{C_{sh}-1}{C_{sh}+1}\right), \tag{5a}$$

$$C_{sh}=Z_{0es}/Z_{0os}, \tag{5b}$$

Similarly, the TZ frequencies can be found from the shunt TL and parallel coupled line, their frequencies can be obtained as in (6).[10]

$$f_{zt}/f_0=(2n-1)/2, \tag{6a}$$

$$f_{zc}/f_0=2n, \tag{6b}$$

where n, f_{zt}, and f_{zc} are an integer and the TZ frequencies generated by the TL and parallel coupled line, respectively.

For a design example of the proposed IT, Z_S = 10 Ω, Z_L = 50 Ω, Z_1 = 30 Ω, and Z_{0es} = 100 Ω are chosen arbitrarily. From (3), the Z_{0e} = 89.724 Ω and 99.7214 Ω are calculated for Z_{0o} = 45 Ω and 55 Ω, respectively. From (4) and (5), the frequencies of the TZs close to the passband are calculated. After calculate Z_{0e}, three transmission poles are observed in the passband by optimizing Z_{0os} and Z_1 of the shunt coupled line and shunt TL. Figure 2 shows the frequency responses of the proposed ITs with different r and Z_{0os}. As shown in Figure 2, bandpass filtering characteristics with high selectivity were obtained. From (6), the TZs produced by $\lambda/2$ TL and parallel coupled line are fixed ($0.5f_0$, $1.5f_0$, $2f_0$, and $2.5f_0$).[10] The TZs produced by the shunt parallel coupled line can be controlled and provide high selectivity. In addition, the TZs can be moved closer to the passband by increasing Z_{0os}. However, the passband bandwidth is then narrowed for the same r to maintain three transmission poles in the passband. A FBW = 18.76% of 20 dB return loss of can be obtained in the case of $r = 5$. Wide and high stopband attenuations can be obtained by five TZs. In the case of $r = 10$, the passband bandwidth is even narrower and higher frequency selective characteristics are obtained. Moreover, the stopband attenuation is increased. However, the required characteristic impedance of the shunt TL is about $Z_1 = 11\ \Omega$, which is difficult to realize with a typical

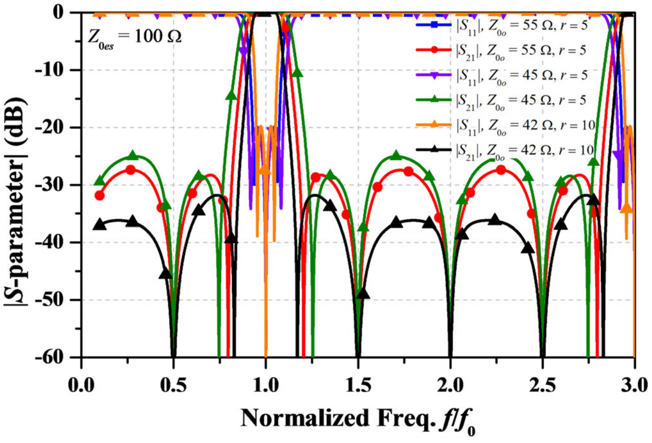

FIGURE 2 Normalized frequency responses of proposed impedance transformer

TABLE 1 Calculated circuit parameters of proposed its with different impedance ratios

	$Z_L = 50\ \Omega, Z_{0es} = 100\ \Omega$		
	$Z_1 = 30\ \Omega, r = 5$		$Z_1 = 11\ \Omega, r = 10$
	$Z_{0os} = 44\ \Omega$	$Z_{0os} = 52\ \Omega$	$Z_{0os} = 58\ \Omega$
	$Z_{0o} = 45\ \Omega$	$Z_{0o} = 55\ \Omega$	$Z_{0o} = 42\ \Omega$
Z_{0e} (Ω)	89.7214	99.7214	73.6228
f_{zcs1}/f_0	0.7457	0.7955	0.8287
f_{zcs2}/f_0	1.254	1.2045	1.1713

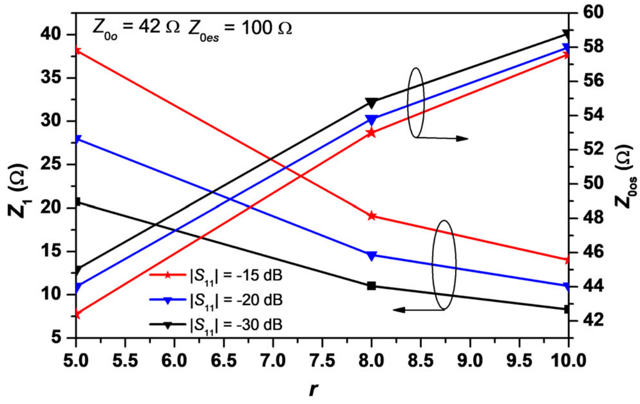

FIGURE 4 Variation of Z_1 and Z_{0os} with different r and magnitude return loss

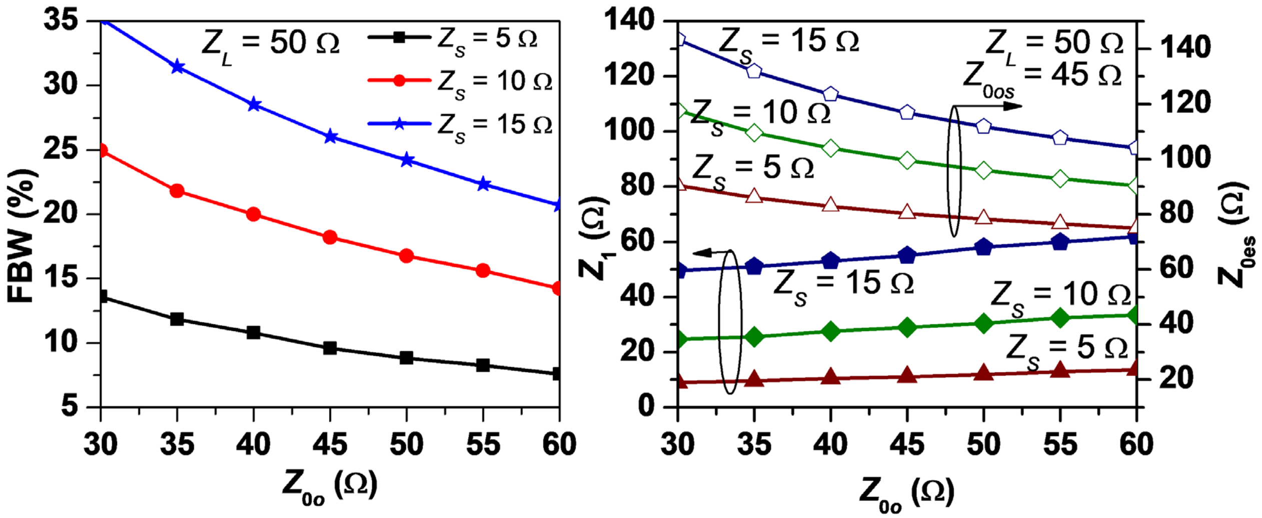

FIGURE 3 Variations of A, FBW of −20 dB return loss, and B, Z_1 and Z_{0es} according to Z_{0o}

microstrip line. The circuit parameters and TZ frequencies were calculated and shown in Table 1. Figure 3A shows the variation of FBW of 20 dB return loss according to Z_{0o} and Z_S. The FBW is decreased as Z_{0o} increases and it is decreased as Z_S decreases. Figure 3B shows the variations of Z_1 and Z_{0es} according to Z_{0o}. Z_1 and Z_{0es} are increased and decreased, respectively, as Z_{0o} increases. Moreover, Z_1 and Z_{0es} are increased as Z_S increases. In Figure 3, the $Z_{0os} = 45\ \Omega$ is chosen. Figure 4 shows the variations of r, Z_1, and Z_{0os} according to magnitude return loss of the passband. The Z_1 is decreased as r increases and it is more decreased as magnitude of return loss is higher. However, the Z_{0os} of shunt coupled line is increased as r increases and it is more increase as magnitude of return loss increases. The $Z_{0o} = 42\ \Omega$ and $Z_{0es} = 100\ \Omega$ are chosen in the simulation.

Figure 5 shows the variations of the TZ frequencies according to Z_{0os} of the shunt parallel coupled line by fixing $Z_{0es} = 100\ \Omega$. The TZs are moved closer to the center frequency as Z_{0os} increases. The TZs being close to the passband improves the selectivity but it may result a narrow passband.

3 | SIMULATION AND MEASUREMENT RESULTS

For experimental verification, 10-to-50 Ω ($r = 5$) and 5-to-50 Ω ($r = 10$) wideband ITs with high selectivity were designed, simulated, and fabricated with $f_0 = 3.5$ GHz. Values of $Z_{0o} = 45\ \Omega$, $Z_{0os} = 44\ \Omega$, $Z_{0es} = 100\ \Omega$,

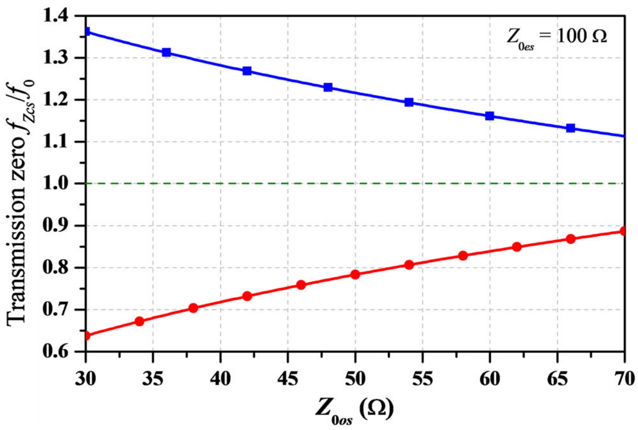

FIGURE 5 Relation between transmission zeros location and Z_{0os}

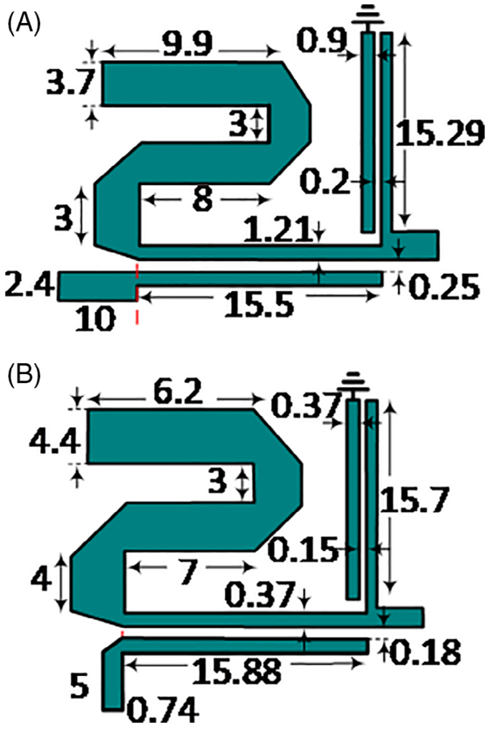

FIGURE 6 EM simulation layouts of proposed IT: A, $r = 5$ and B, $r = 10$. (unit: mm)

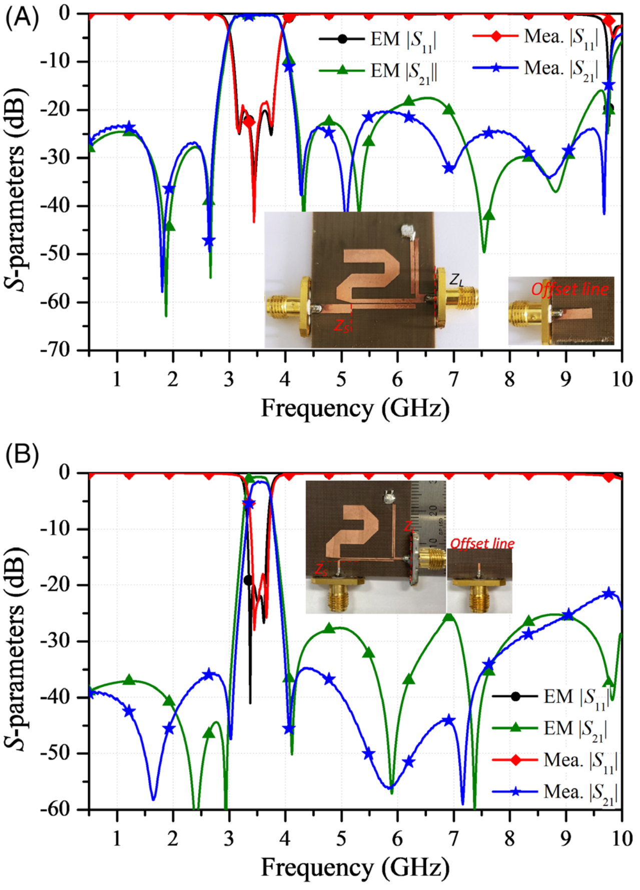

FIGURE 7 EM simulation and measurement results of: A, $r = 5$ and B, $r = 10$

TABLE 2 Performances comparison with previous works

Ref.	**f_0 (GHz)**	**FBW (%)**	**r**	**$\lvert S_{21}\rvert$ (dB)**	**Stop-band Attenuation**	**Freq. selectivity**	**TZ**	**Circuit size $(\lambda_0 \times \lambda_0)$**
[3]	2.6	8.27[b]	10	0.55	DC-0.77f_0/1.26-2.77f_0	No	1	0.26 × 0.22
[4]	1	50[a]	2	0.45	NA	No	NA	0.51 × 0.05
[5]	1.1	120[c]	2	NA	NA	No	NA	NA
[6]	1	60[c]	2	0.82	NA	Yes	2	NA
[7]	2.6	35.38[c]	2	0.4	DC-0.55f_0/1.46-2.56f_0	Yes	4	0.24 × 0.26
[10]	2.6	13.5[c]	5	0.32	DC-0.68f_0/1.33-2.68f_0	Yes	4	0.19 × 0.12
[11]	2.6	4.2[b]	2.5	0.85	DC-0.86f_0/1.15-3.44f_0	No	NA	0.41 × 0.11
This work	**3.5**	**19.85**[b]	**5**	**0.34**	**DC-0.77f_0/1.19-2.78f_0**	Yes	**7**	**0.28 × 0.26**
		7.96[b]	**10**	**1.4**	**DC-0.91f_0/1.11-2.85f_0**			

[a] 15 dB.

[b] 18 dB.

[c] 20 dB return loss.

$Z_1 = 30\ \Omega$ for the parallel and antiparallel coupled lines as well as shunt TL were chosen. The calculated values are shown in Table 1.

The proposed ITs with $r = 5$ and $r = 10$ were fabricated on a substrate with $h = 31$ mils and 10 mils, respectively, and the same $\varepsilon_r = 2.2$. Figures 6A,B show the layouts of the fabricated IT with $r = 5$ and $r = 10$, respectively. The overall circuit sizes are 24 mm × 22 mm ($0.28\lambda_0 \times 0.26\lambda_0$). The method used to measure the proposed IT is mentioned in reference [13].

Figure 7A shows the simulated and measured S-parameters of the proposed IT with $r = 5$. The measured results are comparable with the simulated results. The $|S_{21}| = -0.36$ dB and $|S_{11}| = -28$ dB were measured at $f_0 = 3.5$ GHz. An 18 dB return loss was obtained from 3.112 GHz to 3.807 GHz, which is a FBW of 19.85%. Moreover, the insertion loss within the same passband is better than 0.65 dB. The two transmission zeros close to the passband were measured at 2.65 GHz and 4.28 GHz, and these provide high selectivity. A bandpass frequency response with wide out-of-band suppression was obtained. Lower and higher stopband suppressions of more than 20 dB were measured from DC to 2.77 GHz and from 4.16 GHz to 9.73 GHz, respectively. Moreover, seven TZs were produced in the stopband and provide good stopband performance. Figure 6B shows the simulated and measured S-parameters of the proposed IT with $r = 10$. The $|S_{21}| = -1.4$ dB and $|S_{11}| = -23$ dB were measured at $f_0 = 3.5$ GHz. An 18 dB return loss was obtained from 3.415 GHz to 3.694 GHz, which is a FBW of 7.96%. The two transmission zeros closed to the passband were measured at 3.023 GHz and 4.062 GHz. The deviation of the measured results may cause by the fabrication tolerance of the microstrip coupled lines and TL.

A comparison of electrical performances with other state-of-the-art is summarized in Table 2. As can be seen in Table 2, previous wideband ITs provide either a low r or poor out-of-band suppression. However, the proposed IT provides a wideband, bandpass response with high selectivity, higher r, and wide stopband suppression simultaneously, especially when compared to previous designs. Frequency selectivity of[10] can be obtained with TZs at $0.5f_0$ and $1.5f_0$. However, the frequency selectivity due to the TZ pairs of the proposed work is higher.

4 | CONCLUSION

A bandpass filtering IT with a wideband and high selectivity was proposed in this paper. The design equations of the proposed circuit were derived, calculated, and verified with the simulations and the measurements. The shunt parallel coupled line can produce two controllable transmission zeros (TZs) close to the passband and provide high selectivity. Moreover, the shunt $\lambda/2$ transmission line and the parallel couple line can produce other TZs in the stopband and provide wide stopband performance. Also, the proposed IT has a wide passband with three transmission poles. The proposed IT can be used in RF and microwave circuits which require high impedance transforming and frequency selective characteristics.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available [from] [third party]. Restrictions apply to the availability of these data, which were used under license for this study. Data are available [from the authors / at URL] with the permission of [third party].

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