Design of Wideband Impedance Transformers with Different Number and Different Mounting Positions of the Shunt Stubs

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Abstract In this paper, a novel design method of wideband transmission line impedance transformers is proposed. All the circuit parameters are determined by a self-coded optimization program based on our derived formulas and an appropriately defined objection function. Three microstrip impedance transformers using different number and different mounting positions of the shunt short-circuited stubs are designed with a center frequency of 4.0 GHz and a Chebyshev equal-ripple fractional bandwidth of 80.0%. The measured results agree well with the predicted ones, showing that the proposed design method has adequate freedom in choosing both the number and the mounting positions of the short-circuited stubs, and novel wideband transmission line impedance transformers can be developed with many different configurations.

key words: Impedance transformer, transmission line, shunt short-circuited stub, wideband, microstrip line

Classification: Microwave and millimeter wave devices, circuits, and hardware

1. Introduction

Impedance transformer is one of the important microwave devices used for ensuring the effective operation of many microwave circuits [1][2]. Simple impedance transformers using lumped-element LC circuits are compact and easy to design, but their operation band is very narrow [2]. More complicated designs using mixed lumped elements and distributed networks can achieve broadband property [3-5], but their performance deteriorates with the increase of frequency due to the poor characteristics of lumped LC elements at high frequencies. [6-8] proposed multi-section stepped transmission line impedance transformers with synthesis methods and realized Chebyshev equal-ripple characteristics, but a large number of transmission line sections are needed when wideband operation is wanted. Multi-section/multi-frequency impedance transformers were reported in [9-14], but the improvement of the bandwidth was quite limited. [15] and [16] proposed wideband impedance transformers using multi-section transmission lines and two or more short-circuited stubs. Although the design examples in [15] and [16] showed good performances, the design formulas were quite complicated. In [17-19], open-circuited shunt stubs were employed in the design of compact/dual-band impedance transformers. On the other hand, [20-26] presented impedance transformers using coupled transmission lines to reduce the circuit size and broaden the bandwidth. However, tight-coupling is required for wideband design, which results in small coupling gaps that are difficult to fabricate. In [27] and [28], impedance transformers based on defected ground structures (DGS) were developed at the cost of more complicated design and fabrication procedures. In [29] and [30], multi-layered broadside-coupled stripline structures were used for designing impedance transformers with compact size and wideband operation. In our previous paper [31], we presented a novel design method of a wideband transmission line impedance transformer consisting of four sections of cascaded transmission lines and four symmetrically mounted short-circuited stubs. The paper is significantly revised and extended in this article. In Sec. 2, the proposed impedance transformer and its design method are provided. It includes descriptions of the circuit configuration, analysis method of the circuit, the derived formulas, and an optimization method to determine the circuit parameters. In Sec. 3, three design examples of wideband impedance transformers are demonstrated, all having a center frequency of 4.0 GHz, a fractional bandwidth (FBW) of 80.0%. The first two examples use four short-circuited stubs, one having a symmetrical distribution of these short-circuited stubs and the other having an asymmetrical distribution. The third example...
uses five short-circuited stubs. From these examples, we get the following two important conclusions.
(1) First, the short-circuited stubs can be mounted either symmetrically or asymmetrically to the transmission lines of the impedance transformer. In either case, the impedance transformer can be designed and realize excellent performance of the same level.
(2) Second, different number of short-circuited stubs can be chosen in the design of the impedance transformer, and in all cases, excellent performance of the impedance transformer can be realized. Because of the limited space of this paper, design examples with only four and five stubs are demonstrated, but the conclusion is true with other number of stubs.
From the above conclusions, it is clear that the proposed transmission line impedance transformer can be configured flexibly, and our design method can provide adequate freedom in choosing both the number of short-circuited stubs and their mounting positions on the transmission lines.

2. Circuit configuration and design method

We use the transmission line impedance transformers shown in Fig. 1(a) and (b) as examples to explain our design method. Both transformers in Fig. 1(a) and 1(b) consist of four sections of cascaded transmission lines and four shunt short-circuited stubs, with characteristic impedances of $Z_l$ and $Z_o$ (i=1, 2, 3, 4), respectively. All sections of the transmission lines and short-circuited stubs have an equal electrical length of $\theta$. Also in the figures, $Z_S$ and $Z_l$ indicate the source and load impedance, respectively.

In both impedance transformers, the number of the cascaded sections of transmission lines is fixed as 4. In Fig. 1(a), four short-circuited stubs are symmetrically mounted to the transmission line with respect to the central dash-dotted line, while in Fig. 1(b), four short-circuited stubs are asymmetrically mounted.

The impedance transformer is a two-port network and can be analyzed readily by using the transmission line theory, from which we can derive formulas for determining all the circuit parameters, including the characteristic impedances $Z_l$ and $Z_o$ (i=1, 2, 3, 4), as well as the electrical length $\theta$. Below are brief descriptions of the analysis of the circuits.

The ABCD matrix $[M]$ of the circuit in Fig. 1(a) can be obtained readily by

$$[M] = \begin{bmatrix} A & B \\ C & D \end{bmatrix} = [M_{s1}] \cdot [M_i] \cdot [M_{s2}] \cdot [M_2] \cdot [M_3] \cdot [M_4] \cdot [M_{s4}] \tag{1a}$$

while that of Fig. 1(b) is

$$[M] = \begin{bmatrix} A & B \\ C & D \end{bmatrix} = [M_{s1}] \cdot [M_i] \cdot [M_{s2}] \cdot [M_2] \cdot [M_3] \cdot [M_4] \cdot [M_{s4}] \tag{1b}$$

where $[M_i]$ and $[M_{s1}]$ (i=1, 2, 3, 4) are the ABCD matrix of the transmission line and the short-circuit stub, respectively, and are given by

$$[M_i] = \begin{bmatrix} A_i & B_i \\ C_i & D_i \end{bmatrix} = \begin{bmatrix} \cos \theta & jZ_i \sin \theta \\ \frac{1}{Z_i} \sin \theta & \cos \theta \end{bmatrix} \tag{2a}$$

$$[M_{s1}] = \begin{bmatrix} A_{s1} & B_{s1} \\ C_{s1} & D_{s1} \end{bmatrix} = \begin{bmatrix} \frac{1}{Z_{s1}} \cos \theta & 0 \\ -\frac{1}{Z_{s1}} \sin \theta & 1 \end{bmatrix} \tag{2b}$$

respectively. The difference between (1a) and (1b) is only the multiplication sequence of $[M_{s1}]$ and $[M_{s2}]$, which reflects the change of the mounting position of the third short-circuited stub in Fig. 1(a) and (1b).

Then the transmission coefficient $S_{21}$ between the source impedance $Z_S$ and load impedance $Z_L$ can be obtained through the elements in $[M]$ by

$$S_{21}(\theta) = \frac{1}{\sqrt{1+|A_iB_i+Z_i+C_{s1}D_{s1}-D_{s1}}/Z_S/Z_L} \tag{3}$$

In order to realize a wide passband with Chebyshev equal-ripple characteristics, the following function is chosen as the target function [31]:

$$S_{21}^{\text{Target}}(\theta) = 1/\sqrt{1+|eF_5(\theta)|^2} \tag{4}$$

where

$$F_5(\theta) = \left[ T_5 \left( \frac{\cos \theta}{\cos \theta_c} \right) + aT_3 \left( \frac{\cos \theta}{\cos \theta_c} \right) \right] \sin \theta \tag{5}$$

with

$$a = \left( \sqrt{1/\cos^2 \theta_c - 1} - 1/\cos \theta_c \right) \cos \theta \tag{6}$$

and $T_n(x)$ is the $n$-th order Chebyshev polynomial of the first kind (here we have a fifth-order Chebyshev polynomial), and $\theta$ is the electrical length at the lower equal-ripple edge-frequency of the passband of the circuit, and $\theta_c$ is determined by the value of the required passband return loss.

Next, an object function $F$ below is defined with the circuit parameters $Z_l$ and $Z_o$ (i=1, 2, 3, 4) as the optimization variables.

$$F(Z_l, Z_o) = \sum_{i=1}^{n} \left( S_{21}^{\text{Target}}(f_i) - S_{21}(f_i) \right)^2 \tag{7}$$

where

$$f_i = f_1 + (i - 1) \cdot \Delta f \tag{8}$$

and $f_i$ (i=1, 2, ..., N) are the sampling frequencies in the equal-ripple band of the circuit, and $N$ is the number of...
sampling points used in the simulation.

In the design of the impedance transformer, an optimization program is coded to minimize the value of the above objective function \( F \) in (7), from which, the optimal values of all the characteristic impedances \( Z_i \) of the transmission lines and \( Z_{ai} \) of the short-circuited stubs \((i=1, 2, 3, 4)\) are determined. The electrical length \( \theta \) is determined by the center frequency \( f_0 \) of the passband, and equals to \( \pi/2 \) (a quarter-wavelength) at \( f_0 \).

3. Design examples and measurements

3.1 Two design examples using four short-circuited stubs mounted symmetrically and asymmetrically

At first, two wideband impedance transformers corresponding to Fig. 1(a) and 1(b) are designed, fabricated, and measured, to verify the design method proposed above. The design specifications are as follows. The source and load impedance are \( Z_s = 50.0 \, \Omega, Z_l = 82.0 \, \Omega \), respectively. The center frequency of the passband is \( f_0 = 4.0 \, \text{GHz} \), the minimum return loss in the passband is \( RL = 20.0 \, \text{dB} \) (corresponding to \( \varepsilon = 0.1005 \)), and the equal-ripple passband covers 2.4 \( \sim \) 5.6 GHz (\( \text{FBW} = 80.0\% \)).

Based on the derived formulas (1)-(8), and by using the self-coded optimization program, all the circuit parameters \( Z_i \) of the transmission lines and \( Z_{ai} \) \((i=1, 2, 3, 4)\) of the short-circuited stubs are obtained. In the computation, Eq. (1a) and (1b) are used for the design of the impedance transformer shown in Fig. 1(a) and 1(b), respectively, and the obtained results are summarized in Table I and Table II.

| Table I Optimal circuit parameters for the transformer in Fig. 1(a) when \( Z_s=50.0 \, \Omega \) and \( Z_l=82.0 \, \Omega \) |
|-----------------|--------|--------|--------|
| \( i \)        | 1     | 2      | 3      |
| \( Z_i(\Omega) \) | 47.1  | 76.3   | 91.5   |
| \( Z_{ai}(\Omega) \) | 73.5  | 44.1   | 68.5   |

| Table II Optimal circuit parameters for the transformer in Fig. 1(b) when \( Z_s=50.0 \, \Omega \) and \( Z_l=82.0 \, \Omega \) |
|-----------------|--------|--------|--------|
| \( i \)        | 1     | 2      | 3      |
| \( Z_i(\Omega) \) | 47.1  | 50.6   | 79.5   |
| \( Z_{ai}(\Omega) \) | 77.8  | 62.5   | 45.3   |

Next, the transmission line impedance transformers are designed in microstrip form by using an electromagnetic (EM) simulator based on the above circuit parameters in Table I and II. A dielectric substrate (NIPC260A) with a relative dielectric constant of \( \varepsilon_r = 2.6 \), a loss tangent of \( \tan \delta = 0.0015 \), and a thickness of \( t =1.0 \, \text{mm} \) is used. The EM simulator, Sonnet \( \text{em} \), is used for determining the physical dimensions of the impedance transformers and calculate their responses.

In the case of the impedance transformer with four short-circuited stubs mounted symmetrically, the finally obtained microstrip configuration and geometrical parameters are shown in Fig. 2(a), and a comparison of the circuit and EM simulation responses of the microstrip impedance transformer is given in Fig. 2(b). In the EM simulation, all losses, including the conductor (copper film) loss, the dielectric loss, and the radiation loss of the circuit are considered. The EM simulated performance of the microstrip impedance transformer agrees quite well with the theoretical circuit response. The EM simulated insertion loss is 0.19 dB at 4.0 GHz, while the return loss is better than 20.0 dB at most frequencies within the passband. There are two transmission zeros (TZs) in the frequency property of the proposed impedance transformer, one is at 0 GHz and the other at 8 GHz, which produce sharp skirt of the passband and good selectivity of the impedance transformer.

Fig. 3(a) shows a photograph of the fabricated microstrip impedance transformer with symmetrically mounted four short-circuited stubs. Since the input and output of our measurement system are both 50 \( \Omega \) cables, the 82.0 \( \Omega \) feed line in Fig. 2(a) is replaced with an 82.0 \( \Omega \) chip resistor as shown in Fig. 3(a), and only its return loss \( (S_{11}) \) is measured at Port 1. The measurement is conducted by using an Anritsu MS46122A vector network analyzer. Fig. 3(b) shows a comparison of the measured and EM simulation responses of the microstrip impedance transformer. The agreement is quite favorable.

In the wide passband, the measured return loss is less than 15.7 dB. The measured return loss is larger than the simulated one, and the main considerable reasons are due to the fabrication errors of the circuit including the via-holes to the ground, and due to the parasitic effects of the terminal 82.0 \( \Omega \) chip resistor and its soldering.
In the case of the impedance transformer with four short-circuited stubs mounted asymmetrically, the obtained microstrip configuration and geometrical parameters, the comparison of its circuit and EM simulation responses, are shown in Fig. 4(a) and 4(b), respectively. The photograph of the fabricated microstrip impedance transformer, and the comparison of its measured and EM simulation responses, are shown in Fig. 5(a), and 5(b), respectively. As expected, very good agreement between the simulated results of the design is seen in Fig. 4(b), and good agreement between the EM simulated and measured responses of the microstrip impedance transformer is observed in in Fig. 5(b). In the wide passband, the measured return loss is less than 15.2 dB.

3.2 Design example using five short-circuited stubs
In the third design example, the specifications are the same as those for the above two designs in Sec. 3.1, but the number of short-circuited stubs is changed from four to five. The design method is the same as that described in Sec. 2, with a modification of the ABCD matrix of the circuit as follows:

\[
[M] = \begin{bmatrix}
A & B \\
C & D
\end{bmatrix} = [M_{s1}] \cdot [M_{s2}] \cdot [M_{s3}] \cdot [M_{s4}] \cdot [M_{s5}]
\]

where \([M_i] (i=1, 2, \ldots, 4)\) and \([M_s] (i=1, 2, \ldots, 5)\) are the ABCD matrix of the transmission lines and the short-circuit stubs, shown in Fig. 6(a), respectively. The finally obtained microstrip configuration and geometrical parameters, the comparison of its circuit and EM simulation responses are shown in Fig. 6(a) and 6(b), respectively. The photograph of the fabricated microstrip impedance transformer, and the comparison of its measured and EM simulation responses, are shown in Fig. 7(a), and 7(b), respectively. As expected, very good agreement between the simulated results of the design is observed in Fig. 6(b), and good agreement between the EM simulated and measured responses of the microstrip impedance transformer is found in in Fig. 7(b). In the wide passband, the measured return loss is less than 17.0 dB.
Finally, a comparison of the proposed impedance transformer with previous works is summarized in Table III. Because the design specifications in these works are different, it is not possible to make absolute assessments of these works. However, from the table, it is seen that our work has a few distinctive features. First, the proposed transformer had five in-band reflection zeros (RZs) and two out-of-band transmission zeros (TZs), so it realized a wide passband with low equal-ripple return loss and a good frequency selectivity. The frequency selectivity is indicated in Table III by the roll-off factor, which is usually used in the evaluation of the frequency selectivity of bandpass filters. It is calculated from the difference of attenuations from the passband to the stopband versus the frequencies normalized to the center frequency of the circuit. From Table III, it is seen that the proposed work has a much larger roll-off factor than previous works, meaning a much better frequency selectivity. Second, the proposed designed method is simple to use and is accurate because all the circuit parameters are obtained through a rigorous synthesis approach. Third, the configuration of the proposed impedance transformer is highly flexible, because both the number and the mounting positions of the stubs are free to choose. Finally, the physical structure of our work is simple as only one single-layer substrate is employed. No tiny geometrical dimensions are used so that the proposed impedance transformer can be fabricated easily by low-cost chemical etching method.

### Table III Comparisons of previous works with the proposed impedance transformers

| Ref. | [9] | [15] | [26] | [27] | This work |
|------|-----|------|------|------|-----------|
| ε₀ (GHz) | 1.0 | 2.0 | 1.5 | 0.7 | 4.0 |
| RZs/TZs | 1/0 | 3/2 | 3/2 | 3/0 | 5/2 |
| Equal-ripple | No | Yes | Yes | No | Yes |
| Roll-off factor (dB/100 MHz) | 0.05 | 4.3 | 1.5 | N/A | 8.0 |
| Design method | No synthesis /Simple | Synthesis /Tedious | Cut-and-try | Cut-and-try | Synthesis /Simple |
| Configuration flexibility | No | No | No | No | Yes |
| Structure | 1-layer | 1-layer | 1-layer | 2-layer | 1-layer |
| Minimum dimension | 0.70 mm | 0.54 mm | 0.08 mm | 0.82 mm | 0.40 mm |

### 4. Conclusion

In this paper, a novel design method of wideband impedance transformer is presented. Based on the derived formulas, all the circuit parameters are determined with the assistance of a self-coded optimization program. Three microstrip impedance transformer examples with different number and different mounting positions of the short-circuited stubs are designed, fabricated, and measured, all showing good agreement between the simulated and measured results. It is concluded that the proposed design method has adequate freedom in choosing both the number of short-circuited stubs and their mounting positions on the transmission lines, and this allows us designing high-performance wideband transmission line impedance transformers with many different novel configurations.
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