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A novel quad-band impedance transformer with ultra-high transforming ratio

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ABSTRACT

This paper presents a novel design of ultra-high transforming ratio quad-band impedance transformer. This transformer is capable of matching a very high real load (Z_L) to the source impedance (Z_S) of 50 Ω at four different operating frequencies. The proposed structure is constructed using two series transmission line separated by a H-shaped network. The analytical relationship between various design parameters are obtained using ABCD matrix method to provide a accurate solution. To validate the derived formulas, two prototype of the quad-band transformers with impedance transforming ratios of 10 and 20 are designed, fabricated, and tested. The measured return loss is greater than 15 dB at all operating frequencies. The measured results are consistent with the simulated and theoretical calculations.

1. Introduction

Impedance transformer/matching network is an important part in the design process of microwave systems. The primary work of an impedance transformer is to deliver maximum power, improve signal-to-noise ratio of the system, reduce amplitude and phase errors in a power distribution network. Thus Impedance transformers (ITs) are frequently used in many radio frequency/microwave applications such as antenna feed lines, amplifiers, power dividers, branch line couplers [1–8]. In order to incorporate in advanced communication systems, it is desirable to produce wideband and multi-band ITs for smaller as well as larger load. Many ITs have been designed to match different load for wideband applications [9–14]. In [9], a broadband matching circuit has been developed using symmetric lattice network. A real-to-real matching circuit has been presented using nonuniform transmission line in [10]. An ideal 4:1 Guanella transformer has been modified with coupled lines to obtain a 5:1 broadband impedance transformer [11]. An IT composed of a coupled line and a shunt open stub has been reported for high impedance transforming ratio of 5 [12]. Two open circuited coupled lines connected back-to-back have been employed to design an ultra high transforming ratio IT [13]. This transformer is capable of achieving the impedance transforming ratio of 10 by controlling the coupling coefficient of the coupled lines. In [14], a transforming ratio of 20 has been developed by using a short-end coupled line transformer. Although wideband ITs with ultra-high transforming ratio have been widely reported, but the development of multi-band impedance transformer with ultra-high transforming ratio is still infancy.

In recent years, multi-band and ultra-high transforming ratio (UHTR) impedance transformers are offering fascinating possibilities and constitute significant challenges in the field of modern communication systems [15–26]. Several dual-band [15–21], tri-band [22–24], quad-band [25] and multi-frequency [26] impedance transformers have been developed. In [15], analytical derivations of the two-section IT have been presented to obtained dual-frequency operation. A matching network using two transmission-line has been designed analytically to achieve two arbitrary frequencies [16]. A dual-band Chebyshev IT has been developed by applying two-section transmission-line [17]. In [18], a Π-model has been used to realize a dual-band IT for complex impedance loads. The T-shaped coupled-line has been employed to design a dual-band IT in [19]. An IT employing transmission-lines and shunt stubs has been developed to obtained dual-band operation [20]. In [21], load-healing concept has been used to design dual-band matching network. Multi-section transmission lines [22,23] have been employed to design a tri-frequency impedance transformer for real as well as complex load impedances. In [24], a tri-band matching network for complex load has been designed by a dual-band transformer, transmission line, open-ended and short circuited stubs. Recently, a quad-band transformer has been developed based on multi-section transmission lines for real load impedance [25]. In [26], an adaptive boundary technique has been employed to design multi-frequency matching circuit.

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Although the wideband-transformers with UHTR have been developed in [11–14], its responses were obtained for single operating frequency, limits application in multi-band communication systems. In this paper, we proposed a novel technique to obtain quad-frequency impedance transformer for ultra-high transforming ratio. The key contributions of our work are as follows: (I) Derivation and analysis of a novel quad-band structure terminating to the source impedance of 50 Ω at four different operating frequencies. (II) Employing ABCD matrix method to derive closed form equations for obtaining simple synthesis procedure. (III) Design of the quad-band impedance transformer utilizing modified H-shaped network and discussion to produce flexible operating frequency bands are reported with explicit design plots and tabulations. (IV) Design and demonstration of ultra-high transforming ratio transformers with simple layout are presented and an analysis is made to observe the behavior of the load in the design of quad-band transformer.

2. Analysis of the proposed QBIT network

The schematic diagram of the proposed quad-band impedance transformer (QBIT) is depicted in Fig. 1. Its main aim is to transfer a ultra-high impedance ratio ($r = Z_L/Z_S$) at four operating frequencies. To achieve quad-band performance, the schematic is configured as two series transmission lines combined with a H-shaped network. The characteristic impedance and electrical length of the series lines are Z_1 and θ, respectively. The H-shaped network consists of a series transmission line (Z_3) and four short-ended stubs (Z_2) with the electrical lengths 2θ and θ, respectively. The QBIT is equivalent to a quarter-wavelength transmission line with impedance of Z_X at four different frequencies. This implies the ABCD matrices of the proposed network and a $\lambda_g/4$ transmission line are equivalent, which can be written as:

$$\begin{bmatrix} A_0 & B_0 \\ C_0 & D_0 \end{bmatrix} = M_1 M_2 M_2 M_3 M_2 M_2 M_1 = \pm M_X \tag{1}$$

$$M_1 = \begin{bmatrix} \cos\theta & jZ_1\sin\theta \\ j\frac{\sin\theta}{Z_1} & \cos\theta \end{bmatrix} \tag{2}$$

$$M_2 = \begin{bmatrix} 1 & 0 \\ -j\frac{\cot\theta}{Z_2} & 1 \end{bmatrix} \tag{3}$$

$$M_3 = \begin{bmatrix} \cos 2\theta & jZ_3\sin 2\theta \\ j\frac{\sin 2\theta}{Z_3} & \cos 2\theta \end{bmatrix} \tag{4}$$

By applying matrix inverse properties, Eq. (1) can be rewritten as:

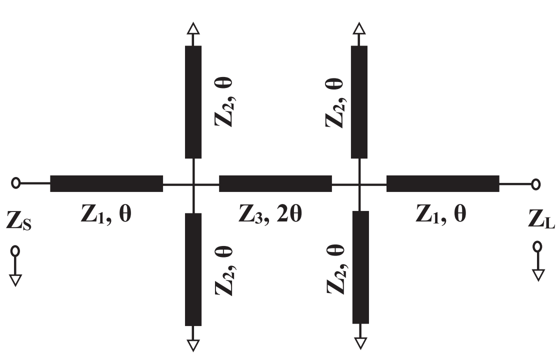

Fig. 1. The topology of the proposed ultra-high transforming quad-band impedance transformer.

$$M_2 M_2 M_3 M_2 M_2 = \pm M_1^{-1} M_X M_1^{-1} \tag{5}$$

$$\begin{bmatrix} K + \frac{4Z_3}{Z_2}M & jZ_3 L \\ j\frac{L}{Z_3} - j\frac{4K\cot\theta}{Z_2} - j\frac{2Z_3 L\cot^2\theta}{Z_2^2} & K + \frac{4Z_3}{Z_2}M \end{bmatrix} = \begin{bmatrix} \left(\frac{D}{Z_1 Z_X}\right)\sin\theta\cos\theta & jZ_X M - j\frac{NZ_1^2}{Z_X} \\ j\frac{M}{Z_X} - j\frac{NZ_X}{Z_1^2} & \left(\frac{D}{Z_1 Z_X}\right)\sin\theta\cos\theta \end{bmatrix} \tag{6}$$

where

$$K = \cos 2\theta,\ L = \sin 2\theta,\ M = \cos^2\theta, \quad \textit{and} \quad N = \sin^2\theta$$

$$D = Z_1^2 + Z_X^2,\ Z_X = 50\sqrt{r}$$

By solving Eq. (6), the closed form design equations are derived as follows:

$$Z_2 = \frac{2Z_1^3}{Z_X^2}\left[\frac{D}{Z_X^2 - Z_1^2}\right] \tag{7}$$

$$Z_3 = \frac{DZ_1}{2Z_X^2} \tag{8}$$

$$f_{c2} = f_{c1}\frac{S_2}{S_1} \tag{9}$$

$$f_{c3} = f_{c1}\left[\frac{\pi}{S_1} - f_{c1}\right] \tag{10}$$

$$f_{c4} = f_{c1}\left[\frac{\pi}{S_2} - 1\right] \tag{11}$$

where

$$S_1 = \tan^{-1}\left[\frac{Z_X}{Z_1}\left(\sqrt{1 + \frac{D^2}{4Z_X^4}} - \frac{D}{2Z_X^2}\right)\right] \tag{12}$$

$$S_2 = \tan^{-1}\left[\frac{Z_X}{Z_1}\left(\sqrt{1 + \frac{D^2}{4Z_X^4}} + \frac{D}{2Z_X^2}\right)\right] \tag{13}$$

$$\theta = \frac{\pi f_{c1}}{f_{c1} + f_{c4}} \tag{14}$$

A simple design approach for quad-band impedance transformer can be briefed as:

1. First, specify the values of source impedance Z_S and transforming ratio r. For $Z_S = 50\ \Omega$, calculate the value of $Z_X = 50\sqrt{r}\ \Omega$.
2. The first central frequency f_{c1} is assumed, for a particular value of Z_1, other central frequencies f_{c2}, f_{c3}, and f_{c4} can be obtained using Eqs. (9)–(11).
3. Using Eqs. (7) and (8), compute the values of Z_2 and Z_3, if these values are beyond the realization limit of microstrip technology, go back to step 2 and select a suitable value of Z_1.
4. The electrical length θ can be determined from Eq. (14).
5. The physical dimensions are computed at f_{c1}.

Following the above synthesis approach, the required design parameters are calculated from the transcendental Eqs. (7)–(14). The values of Z_2 and Z_3 are computed using Eqs. (7) and (8), respectively. These two equations determine the limit of the Z_1 for a particular load impedance. For example, the relationship between Z_1 and the other characteristic impedances (Z_2 and Z_3) can be observed from Fig. 2. From the plot, it is observed that the value of Z_2 and Z_3 is increasing with the increase of Z_1. As Z_1 approaches