

Design of Nonuniform Transmission Lines using Electromagnetic Inverse Scattering

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Abstract

A novel analytical approach for the reconstruction of physical structures of a non-uniform transmission line is presented. The method is based on the analytical solution of the corresponding inverse scattering problem, and involves the reconstruction of the impedance profile in terms of the measured frequency response of the test medium.

Keywords: Inverse Problems, Nonuniform Lines, Electromagnetic Scattering

1. Introduction

The reconstruction of non-uniform transmission line has been shown to have wide range of applications in areas such as filters, couplers, power dividers, pulse transformers, resonators, impedance matching devices etc [1] [2]. The basic idea here is to detect any discontinuity along the line by carrying out measurements at surface of the object or media. The time domain reflectometer (TDR) is one of the most commonly used device for finding the discontinuity along the line. However, its use is mainly restricted to step discontinuity, and hence the continuously varying transmission lines can not be synthesized using this approach. Moreover, the TDR approach does not take into account the multiple reflections along the line, which limits its accuracy for many practical applications.

An alternative approach to find the discontinuity along the transmission line is to carry out measurements of the scattering coefficient data in the frequency domain, and then make use of the integral transform approach in order to obtain the parameter under test in the spatial domain. This approach is usually called the inverse procedure as the properties of the object or the device under test in this case can not be obtained using any direct methods. The main advantage of using the inverse scattering procedure is that even lines of the continuously varying impedance profile can be reconstructed. In recent times, a number of authors have tried to make use of the inverse scattering procedure in order to analyze and reconstruct nonuniform microstrip lines [1]. However, the inverse scattering methods employed by most of the authors in the past make use of some numerical techniques, which quite often leads to non-linearity and ill-posedness.

In this work, the electromagnetic inverse scattering approach has been employed for the design and synthesis of continuously varying transmission lines. The main advantage of the proposed approach as compared to that of the other inverse methods for the reconstruction of nonuniform transmission lines is that our approach provides a closed form analytical solution of the corresponding inverse problem. The proposed inverse scattering reconstruction algorithm is based on the solution of the Riccati nonlinear differential equation, which has successfully been applied in the field of microwave imaging and sensing [3] [4]. The basic idea here is to solve the Riccati differential equation using the innovative renormalization procedure [3], and then develop a novel reconstruction algorithm in order to obtain a closed form expression of the continuously varying impedance profile in terms of the inverse Fourier transform of the measured spectral domain reflection coefficient data.

In this paper, first of all, the theory of inverse scattering making use of the Riccati differential equation is revisited, and accordingly closed form expressions required for the synthesis of nonuniform planar lines are derived. The derived expressions are then employed to reconstruct a number of impedance profiles and nonuniform microstrip lines in order to validate the proposed technique. Finally, a number of nonuniform microstrip lines are fabricated, and the measured scattering data of these lines are found to be in good agreement with the theoretical values.

2. Theory

A. The Riccati type equation for the direct problem formulation

The exact riccati differential equation for the reflection coefficient corresponding to one dimensional planar structure can be expressed as [5]

$$\frac{d\Gamma(k_0, x)}{dx} = 2j\beta\Gamma(k_0, x) - \frac{1}{2}(1 - \Gamma^2(k_0, x)) \frac{d(\ln \bar{Z}(x))}{dx} \quad (1)$$

Where $\Gamma(k_0, x)$ is the local reflection coefficient, $\bar{Z}(x)$ is the normalized local characteristic impedance, $\beta(k_0, x)$ is the local propagation constant describing the wave propagation in the x-direction, and k_0 is the free-space wave number of a monochromatic plane wave. The normalized impedance and the propagation constant of wave are related to the impedance and the wave number according to

$$\bar{Z}(x) = \frac{Z(x)}{Z_0} \ \& \ \beta(x) = \frac{k_0}{\bar{Z}(x)} \quad (2)$$

It can be observed that (1) is a nonlinear equation, which does not have a general solution. Although, for the direct problem, it can be solved numerically for a given impedance profile in order to obtain frequency dependent reflection coefficient data using appropriate boundary conditions. However, to obtain inverse solution which is the main goal of this paper, the equation (1) can not be directly integrated.

B. The inverse solution

For obtaining the inverse solution of (1), the renormalization technique recently proposed in [3] [4] has been employed. The solution requires integration of renormalized form of (1) from infinity to a finite point x, which is then simplified by assuming a matched load condition at infinity (usually applicable for most practical applications). In actual situation, one usually measures the reflection coefficient at the input side $\hat{\Gamma}(k_0, 0) = \hat{R}(k_0)$, and for this case the integration can be simplified to have the following form:

$$\hat{R}(k_0) = -\int_0^\infty \left\{ -\frac{1}{2\bar{Z}(x)} \frac{d\bar{Z}(x)}{dx} \exp\left[\int_0^x -j2\frac{k_0}{\bar{Z}(x')} dx' \right] \right\} dx \quad (3)$$

It can be seen from the above equation that it is not possible to separate the spectral and spatial variables explicitly because of the presence of $\frac{1}{\bar{Z}(x)}$ term. For this purpose, the concept of electrical length can be introduced as

$$l = 2\int_0^x \frac{1}{\bar{Z}(x')} dx' \quad \& \quad dl = \frac{2}{\bar{Z}(x)} dx \quad (4)$$

The variable l can then be substituted in (3) to obtain

$$\hat{R}(k_0) = \int_0^\infty \left[\frac{1}{4} \frac{d\bar{Z}(x)}{dx} \right] \exp[-jkl] dl \quad (5)$$

On solving (5), we arrive at following equation

$$\bar{Z}(l) = \bar{Z}(0) \exp\left[2\int_0^l \hat{r}_0(l') dl' \right] \quad (6)$$

Where $\hat{r}_0(l')$ is the Fourier transform of $\hat{\Gamma}_0(k_0)$, which is the virtual reflection coefficient corresponding to $\Gamma_0(k_0)$ [3]. Equation (6) gives the impedance profile $Z(l)$ in terms of the

electrical length. The electrical distance l can be converted into the physical distance x using a numerical algorithm based upon the following equation:

$$x_n = \frac{cl_n}{2\sqrt{\epsilon_e}}, \quad n=0,1,2,\dots,N \quad (7)$$

Where l_n corresponds to x_n , c is velocity of light in free space, ϵ_e is effective permittivity.

2. Simulation Results

The proposed technique is first validated by considering a 3 layered impedance profile as shown in Fig. 1(a). The figure shows the comparison between the actual and reconstructed profiles using the proposed approach. The reflection coefficient data for this case lie in the range of 0 to 30GHz with the step size of 50MHz. After considering the generalized impedance profile, a nonuniform microstrip lines is reconstructed using the proposed approach. The structure is simulated using the CST Microwave Studio [6] on FR-4 substrate having a relative dielectric constant $\epsilon_r = 4.4$. The simulated S11 response is then used in the proposed reconstruction to obtain the impedance profile, which is then converted to the width of the microstrip lines using the standard empirical relations [7]. Fig. 1(b) shows the comparison of the actual and the reconstructed width profiles for the line, where it can be observed that the reconstructed width is in very good agreement with the actual width of the microstrip line.

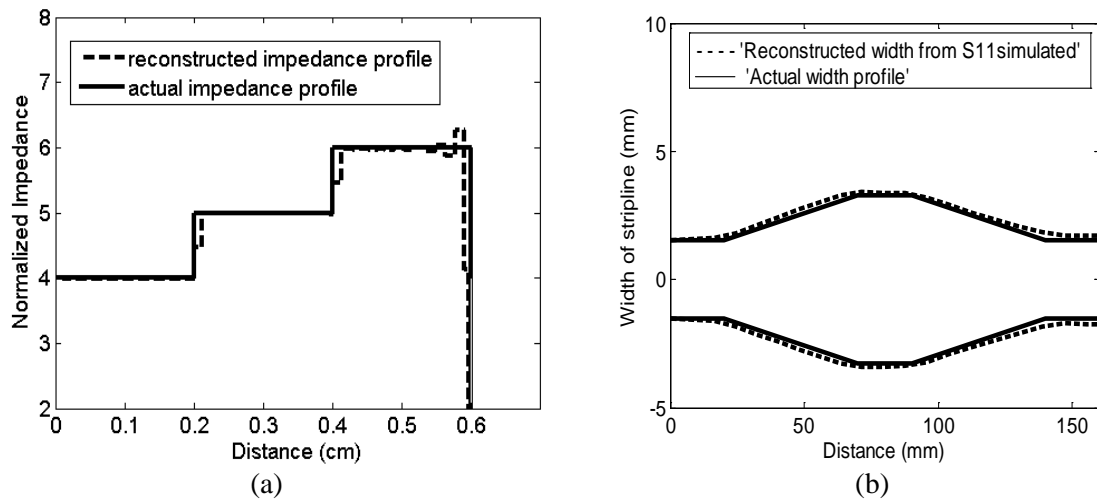


Figure 1: (a) Actual and Reconstructed three layered impedance profiles (b) The comparison of actual and reconstructed impedance profile for the FR-4 microstrip line

3. Measured Results

After validating the proposed method against the simulated data, two microstrip lines are fabricated. The variation of the characteristic impedance and the width of these two lines as a function of length is shown in Figs. 2 (a) & (b). These two microstrip lines are fabricated on a substrate having a relative dielectric constant $\epsilon_r = 2.18$, and thickness $h = 0.7874$ mm. The scattering coefficients of the fabricated line are measured using the N5230C PNA-L Vector Network Analyzer. The measured reflection coefficient data is then used in the proposed reconstruction algorithm to obtain the impedance profile of the lines, which are then converted into width of the microstrip line using standard empirical relations [7]. Fig. 3(a) shows comparison between the actual width of the line, and the width profile reconstructed using the-measured reflection coefficient data of the first fabricated line. Fig. 3(b) shows the comparison between the simulated and the measured S-responses for the second line, where simulated data is obtained using an independent 3-D electromagnetic field simulator, the CST Microwave studio (CST) [6]. It can be observed from both Figs. 3(a) & 3(b) that a very close agreement exists between the actual/simulated and the measured parameters

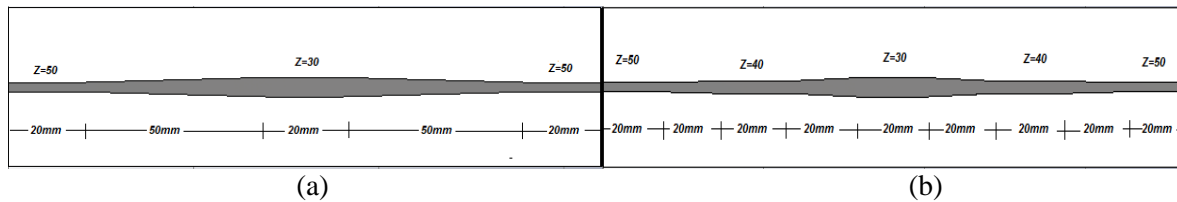


Figure 2: The physical layouts of two nonuniform microstrip.

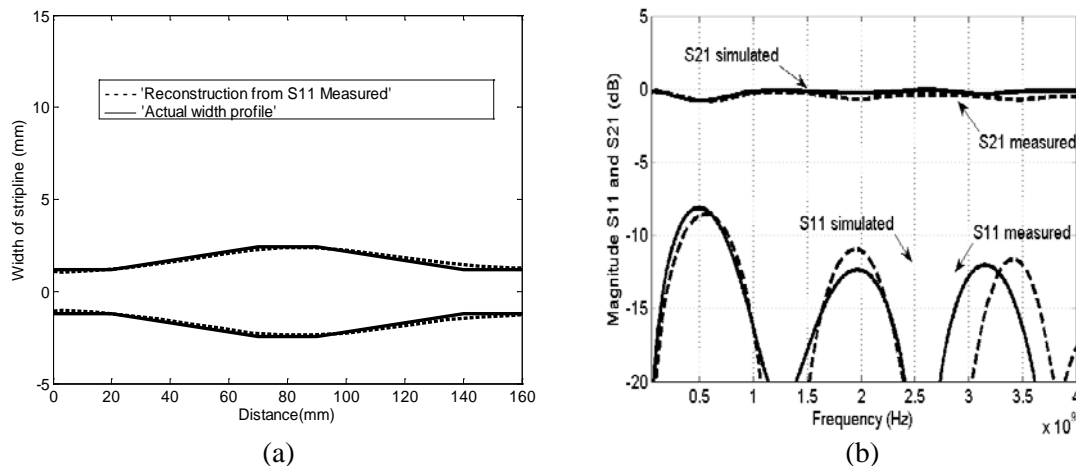


Figure 3: (a) The comparison of the actual width profile, the width profile reconstructed from S11 measured and the width profile reconstructed from S11 simulated for first line (b) The comparison of simulated and measured S responses for the second line.

It is clear from the above examples that the proposed technique can quite conveniently be employed to reconstruct a nonuniform microstrip line with a reasonably higher amount of accuracy.

4. Conclusion

A novel approach to design the physical layout of nonuniform microstrip lines has been presented. The proposed approach takes into account multiple reflections inside the line, and the microstrip lines having continuously varying impedance profile can quite accurately be reconstructed. A number of practical design examples have been considered in order to show the applicability of the proposed scheme. In the present work, the proposed approach is mainly applied for the microstrip lines, but the overall technique is quite general and can equally be applied to other types of transmission lines.

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