Synthesis of Hecken-Tapered Microstrip to Paralell-Strip Baluns for UHF Frequency Band

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***Abstract*— Microstrip to Parallel-Strip transitions are frequently used for feeding balanced antenna structures, such as dipoles and printed spiral antennas. In this paper, we propose an analytical method to compute the gradual taper using a Hecken approach in order to minimize the return losses and to have continuity. The proposed method is verified experimentally with the aid of three transitions including matching capabilities with different ratios, suitable for spiral antenna structures in, at least, the ranges from 450 MHz to 2 GHz.**

***Index Terms*— Balun, parallel-strip line, taper.**

I. Introduction

The design process of millimeter integrated circuits with balanced and unbalanced devices must be performed carefully because it usually implies transitions between both types of circuits called baluns. This may include impedance matching capabilities, which are required, for example, when a parallel-strip antenna is connected to a microstrip line.

Printed parallel-strip lines (PSTL), as balanced structures, offer an interesting alternative to other printed transmission lines, such as the coplanar stripline, or to other unbalanced transmission structures such as the common microstrip line. PSTLs are naturally balanced, without a ground plane, making them suitable for designing both, passive and active microwave circuits. Additionally, they are used in antenna designs when almost omnidirectional radiation patterns are required, avoiding the possible complexities of microstrip antenna designs in order to achieve those patterns.

The first balun geometry using the PSTL was proposed by Climer [1] and since then, this balun has been used for years in order to measure some antennas, couplers, feeding networks, and other balanced circuits. As recent examples of such circuits, printed filters and couplers are designed in [2], a band-pass filter is developed in [3] by inserting a ground plane between the strips, and [4] shows a diplexer based on a similar configuration.

This paper develops a novel analytical method which provides good performance used for the design of parallel-strip to microstrip tapered baluns. The approach is based on analytical formulas proposed in [5] and the Hecken taper [6] to compute the ground shape to achieve low return losses with continuity in the boundary junctions (either PSTL o Microstrip lines). The method requires the knowledge of the characteristic impedances which are related to the Hecken impedance values, and provides the geometric design by solving certain algebraic equations which are derived in the paper. Finally, three baluns with different matching ratios are synthesized with the proposed method, are analyzed by a Finite Element Method (by means of HFSS) and the prototypes are tested using a Vector Network Analyzer.

II. Theoretical Transition Analysis

The microstrip (MS) to double-sided parallel strip (PS) tapered transition geometry consists of a (finite) ground plane which is gradually converted into a strip, as it is showed in Fig. 1. The double-sided parallel line is achieved when the final strip is exactly identical in width to the non-ground plane strip. According to the results presented in [1], the electromagnetic performances of this transition depend on the taper applied in the gradual ground plane conversion. From the physical point of view, this taper sets the characteristic impedance at any position along the balun. Therefore, the reflected power depends on this variation in Z_0.

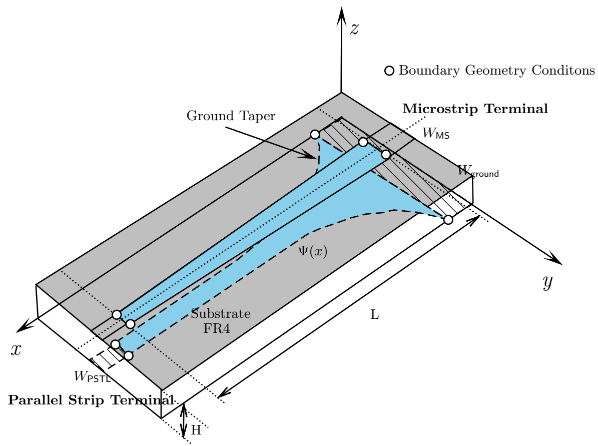

Fig. 1. PSTL-MS Tapared Balun Geometry and its parameters.

A. Tapered Balun Return Loss Perfomance

The parallel-strip to microstrip geometry can be analyzed as a particular case of a non-uniform transmission line in quasi-TEM operation. Several authors have studied (in frequency and time domain) different methods to accomplish the evaluation of the performance in terms of the reflection coefficient, $\rho(x)$, which is modeled in the case of tapering by the following Ricatti type nonlinear differential equation

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$$\frac{d\rho}{dx} - 2\gamma\rho + \frac{1}{2}\left(1-\rho^2\right)\frac{d(\ln \overline{Z})}{dx} = 0 \tag{1}$$

where γ is the propagation constant and $\overline{Z}(x)$ is the normalized impedance, which is a function of the distance x along the taper. Its solution is not simple, but if $\rho^2 \ll 1$ is assumed and ohmic losses and dispersion are considered negligible ($\gamma = j\beta$), can be cast as a Fourier Transform

$$\rho(\beta) = \frac{1}{2}\int_0^L e^{-j2\beta x}\frac{d}{dx}(\ln \overline{Z})dx \tag{2}$$

where L is the total transition length, $\beta = \frac{2\pi f\sqrt{\epsilon_{\text{eff}}}}{c}$ is the effective propagation constant, f is the frequency, c is the speed of light and ϵ_{eff} is the effective dielectric constant (assumed to remain unchanged as a first approximation).

The normalized impedance $\overline{Z}(z)$ is the magnitude which links the electrical performance with the physical parameters. Therefore, the ground plane taper can be computed for a specified reflection coefficient by doing a staircase approximation in sections and defining their required impedance.

B. General Impedance Formula in Quasi-TEM regime

In order to perform the synthesis, we must focus on the study of asymmetrical double-sided strip lines (as Fig. 2). The dielectric sheet is assumed to be infinitely wide, and the strips have negligible thickness. The structure is closed by an infinite ground plane because the impedance expression comes out from the conformal mapping technique, following a similar process to the one employed in a microstrip line analysis. The geometry resembles a microstrip line of $W = 2b$ in width when $a \to \infty$, whereas if $a = b$ the parallel-strip line is obtained.

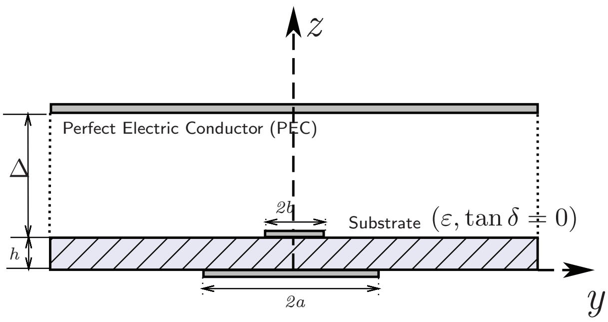

Fig. 2. Transversal cut to compute the characteristic impedance

The characteristic impedance and the effecive dielectric constant are given, supposing a quasi-TEM mode by [5]

$$\epsilon_{\text{eff}} = \frac{C}{C_0} = \frac{\frac{K(\vartheta')}{K(\vartheta)} + \epsilon_r \frac{K(\alpha')}{K(\alpha)}}{\frac{K(\vartheta')}{K(\vartheta)} + \frac{K(\alpha')}{K(\alpha)}} \tag{3}$$

and

$$Z_0 = \frac{60\pi}{\sqrt{\epsilon_{\text{eff}}}\left(\frac{K(\vartheta')}{K(\vartheta)} + \frac{K(\alpha')}{K(\alpha)}\right)} \tag{4}$$

where $K(\lambda)$ is the complete elliptical integral

$$K(\lambda) = \int_0^{\pi/2}\frac{dx}{\sqrt{1-\lambda^2\sin^2 x}} \tag{5}$$

and

$$\vartheta = \text{sech}\left(\frac{\pi b}{2\Delta}\right) \quad \vartheta' = \sqrt{1-\vartheta^2} \tag{6}$$

$$\alpha = \sqrt{\frac{2(x_a+x_b)}{(1+x_b)(1+x_a)}} \quad \alpha' = \sqrt{1-\alpha^2}$$

$$x_a = \cosh\left(\frac{a\pi}{h}\right) \quad x_b = \cosh\left(\frac{b\pi}{h}\right) \tag{7}$$

As a thumb's rule, the value of Δ is approximately chosen to be 20 h and, once the desired characteristic impedance is known, the remaining task is to compute the values of a and b. As far as the synthesis is concerned, the top layer is fixed with a linear taper, and consequently the value of b is known a priori for each section. Using the previous analysis we can solve the equations to obtain the value of a, and, finally, build the staircase ground shape.

III. Hecken Taper Design Proceduce

Before designing the transition geometry, designers need, among other values, the reflection coefficient requirements. There is usually a tradeoff between the total length or size of the structure and the return losses. Thus, one possible criterion might be to choose the optimum solution to that compromise. In addition, the input and output impedances (or the input/output impedance and transform ratio) are also required.

The optimum impedance taper corresponding to a fixed length matching section has been analyzed by several authors. Using the integral formulation, Klopfenstein [7] showed the optimum taper in the sense that the minimum reflection coefficient for a passband fulfills

$$\ln Z(x) = \frac{1}{2}\ln Z_0 Z_L + \frac{\Gamma_0}{\cosh A}A^2\phi\left(\frac{2x}{L}-1, A\right), 0 \le x \le L \tag{8}$$

where the function $\phi(x, A)$ is defined as

$$\phi(x, A) = -\phi(-x, A) = \int_0^x \frac{I_1(A\sqrt{1-y^2})}{A\sqrt{1-y^2})}dy, \quad \|z\| \le 1 \tag{9}$$

I_1 being the modified Bessel function, A the value defining the passband fulfilling the condition $\beta L > A$, and Γ_0 the bound of the reflection coefficient in the passband.

Although the Klopfenstein taper is the optimum in the explained sense, it does not provide continuity at the microstrip and parallel strip ports. Therefore, the final performance can

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be degraded. To solve this drawback, Hecken modified slightly the reflection coefficient expression that leads to impedance values which must fulfill

$$\ln Z(x) = \frac{1}{2}\ln Z_0 Z_L + \frac{1}{2}\ln\left(\frac{Z_L}{Z_0}\right)\Phi\left(A, \frac{2x}{L}\right), 0 \leq x \leq L \tag{10}$$

where $\Phi(A, \eta)$ is the function defined by

$$\Phi(A, \eta) = \frac{A}{\sinh A}\int_0^{\eta} I_0\left(A\sqrt{1-u^2}\right)\, \mathrm{d}u \tag{11}$$

the constant A is computed by means of the same condition than that of Klopfenstein Taper through the specified balun length L.

The synthesis algorithm combines eqs. (4-7) and eqs. (10-11) to impose a Hecken response in the reflection coefficient. The method comprises the following steps:

1) Step 1: the algorithm begins with the calculation of the boundary geometrical parameters (W_{MS} and W_{PSTL}) using the required input and output impedances Z_{MS} and Z_{PSTL}. This task is carried out using design equations for microstrip and parallel strip lines, or alternatively, by means of eq. 4.

2) Step 2: specify the total balun length, *L*. This length should be at least $\lambda_g/4$, being λ_g the wavelength corresponfing to the minimum operative frequency. Next, the constant *A* can be computed in order to determine the Hecken impedances according to

$$\beta L \geq A \longrightarrow A \leq \frac{\pi}{2} \tag{12}$$

3) Step 3: perform a suitable partition of the interval $[0, L]$ in sections placed at x_i coordinates that will define the staircase approximation. One different Hecken impedance will correspond to each different section.

4) Step 4: compute the top layer taper. The usual and easiest approach applies a linear taper because the boundary restrictions are often very close. The linear taper is defined by two different constants *M,N* such that, if $b(x) = Mx + N$, are computed using the following conditions:

$$b(0) = \frac{W_{\mathsf{MS}}}{2} \quad b(L) = \frac{W_{\mathsf{PSTL}}}{2} \tag{13}$$

that leads to

$$M = \frac{W_{\mathsf{PSTL}} - W_{\mathsf{MS}}}{2L} \quad N = \frac{W_{\mathsf{MS}}}{2} \tag{14}$$

5) Step 5: compute the ground plane layer taper. The required impedance for every i-subsection, Z_i^H is established by means of eq. (4-7) and eq. (10-11). First, notice that the top layer strip width has been fixed in step 4 and thus the determination of the bottom layer strip width $a(x)$ may be accomplished by solving

$$Z_i^H = \frac{60\pi}{\sqrt{\epsilon_{eff}}\left(\frac{K(\vartheta')}{K(\vartheta)} + \frac{K(\alpha')}{K(\alpha)}\right)} \tag{15}$$

To simplify notation, let us call $\eta_i = \frac{K(\alpha')}{K(\alpha)}$ and $\lambda_i = \frac{K(\vartheta')}{K(\vartheta)}$ where the former is the unknown variable and the later is a defined number. After some algebraic manipulations, eq. (15) is equivalent to solve

$$\varepsilon_r \eta_i^2 + (\varepsilon_r + 1)\lambda_i \eta_i + \lambda_i^2 - \left(\frac{60\pi}{Z_i^H}\right)^2 = 0 \tag{16}$$

Eq. (16) has two possible roots but only the real positive value is valid since η_i must always be greater than zero. If η_{r_i} is the root, then α_{r_i} is the solution of

$$\eta_{r_i} = \frac{K\left(\sqrt{1-\alpha_{r_i}^2}\right)}{K\left(\alpha_{r_i}\right)} \tag{17}$$

which has not analytical close-form. However, it can be solved easyly with the aid of numerical methods. Finally, once α_{r_i} is known, the required value to find the Hecken shape, $a(x_i)$ is derived from eq. (7)

$$\alpha_{r_i} = \sqrt{\frac{2(x_a + x_b)}{(1 + x_b)(1 + x_a)}} \tag{18}$$

which, after some manipulations results in

$$a(x_i) = \frac{h}{\pi}\operatorname{arccosh}(\zeta(x_i)) \tag{19}$$

where

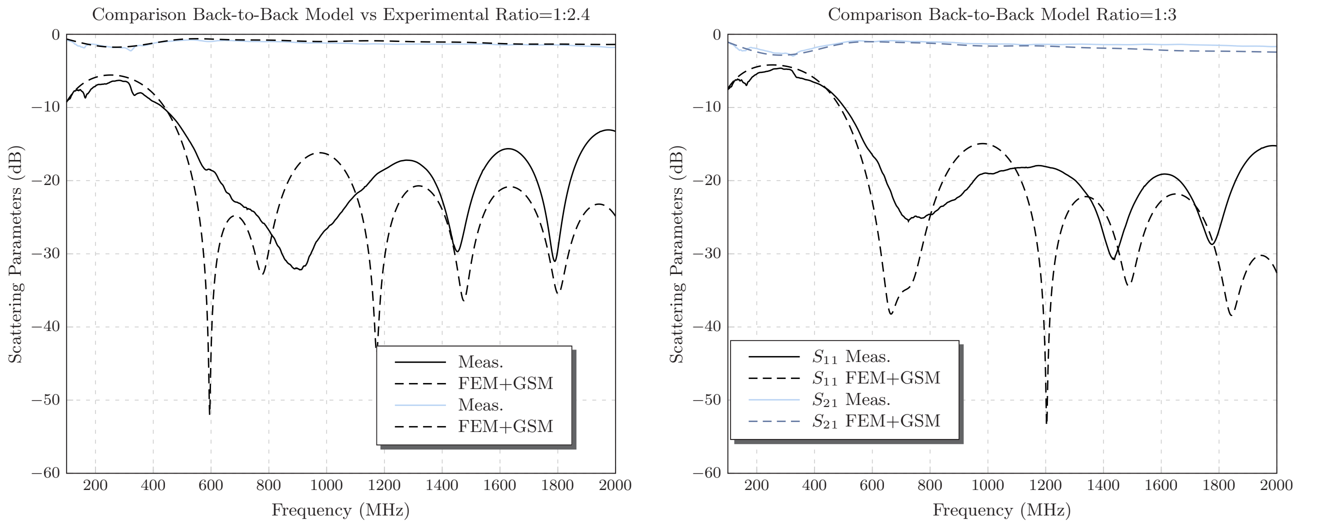
$$\zeta(x_i) = \frac{\alpha_{r_i}^2 + (\alpha_{r_i}^2 - 2)\cosh\left(\frac{b(x_i)\pi}{h}\right)}{2 - \alpha_{r_i}^2 + \alpha_{r_i}^2\cosh\left(\frac{b(x_i)\pi}{h}\right)} \tag{20}$$

As an example of the algorithm outputs, Table I contains the numerical synthesized values with the proposed method in the case of a transition which matches 50Ω to 155Ω in a FR4 substrate with $\varepsilon = 4.6$ and $H = 1.54$ mm

TABLE I

NUMERICAL OUTPUTS OF THE HECKEN TAPERED TRANSITION

x_i **coordinate** (mm)	$b(x_i)$	$a(x_i)$	**Impedance** (Ω)
0	1.6000	4.3024	49.9737
11.5000	1.4650	2.4844	54.4905
23.0000	1.3300	1.9091	60.4300
34.5000	1.1950	1.5081	67.9471
46.0000	1.0600	1.1954	77.1467
57.5000	0.9250	0.9475	88.0341
69.0000	0.7900	0.7450	100.4579
80.5000	0.6550	0.6000	114.0593
92.0000	0.5200	0.4959	128.2476
103.5000	0.3850	0.4513	142.2266
115.0000	0.2500	0.5044	155.0815



(a) (b)

Fig. 3. Electromagnetic performance comparison between full-wave simulations and the experimental results.(a) back-to-back $50\Omega - 120\Omega$ Hecken Balun. (b) back-to-back $50\Omega - 155\Omega$ Hecken Balun.

IV. Full Wave Analysis and Experimental Results

In order to validate the synthesis method, three test samples of $\lambda_g/4$ in length corresponding to matching ratios of $1:2.4$ $1:3$ and $1:3.6$ have been designed on a FR4 substrate with dielectric constant 4.6 and to operate above 450 MHz (UHF band). Measurements have been carried out in a back-to-back configuration because of the balanced circuit nature. Since it is not straightforward to characterize by measurements a single balun, we have also performed an electromagnetic simulation with HFSS (FEM method) and, using a combining approach of two single balun scattering matrices (Generalized Scattering Matrix Method), the total back-to-back configuration response has been obtained. These results are compared with experimental data (Fig. 3a and Fig 3b), which are obtained by means of the vector network analyzer ANRITSU 37247D (Fig. 4 presents the manufactured boards). A good agreement between simulation and experimental results are obtained, and return loss below -10 dB above the specified frequency is obtained in all designs.

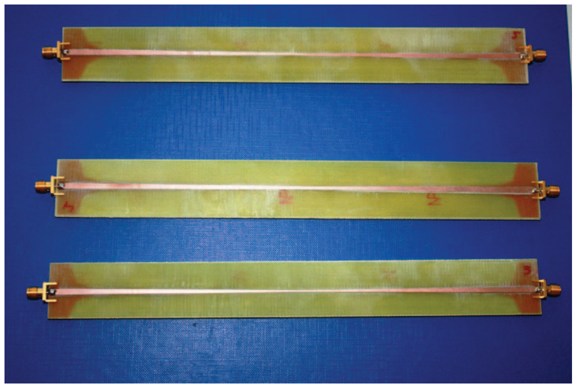


Fig. 4. Examples of Hecken Transitions designed by the proposed method

V. Conclusion

In this paper, we have proposed an analytical method based on the Hecken taper and a closed-form expression for the characteristic impedance of a non-uniform transmission line to design transitions suitable for UHF frequency band (as long as the quasi-TEM condition together with low loss suposition remains accurate). Finally, the approach has been tested on real samples which have been simulated using the FEM method and measured with a Vector Analyzer, showing a suitable response in terms of return losses for the specified frequency band.

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