Synthesis of Nonuniform TEM-Mode Directional Couplers with Arbitrary Coupling Response

M. R. Pereira* H. M. Salgado† J. R. Pereira‡

Abstract — **We propose the use of inverse scattering on the design of ultra wide band nonuniform coupled line directional couplers with a specified coupling response. The inverse scattering is performed using the layer peeling algorithm which is simple and of easy implementation as a computer routine. To validate the method a wide band directional coupler is designed and implemented.**

1 INTRODUCTION

The wave propagation along sets of parallel conductors is a subject that has been investigated since the early ninety's. The first full mathematical analysis of transmission line directional couplers was performed in 1954 by Oliver [1]. Until then, and related with the problem of crosstalk, energy coupling between parallel conductors was regarded as an undesired phenomena. Therefore, all the research was focus on eliminating the coupling problem, rather then using it in all of its potential.

In his work, Oliver made a full mathematical analysis of the natural coupling between parallel transmission lines and was able to foresee the potential applications of such devices such as directional couplers, filters and transformers.

Later, in 1963, Young [2] has shown that every cascaded transmission line directional coupler has a cascaded stepped impedance transformer prototype, and that the reflection coefficient of this prototype is identical to the coupling coefficient of the cascaded directional coupler. Similarly, the transmission coefficient of the stepped impedance prototype is also identical to the transmission coefficient of the directional coupler.

As the work of Young strongly suggests, the design of directional TEM-mode coupling devices reduces to that of the so-called impedance transformer prototype which is nothing more than a nonuniform transmission line (NTL).

Recently, we have proven that inverse scattering is a very useful tool for the synthesis and design of nonuniform transmission line microwave filters [3]. In fact, we have shown that inverse scattering allows for the synthesis of any physically realizable frequency response. Also the possibility of arbitrary reflection group delay response is reported in [4], where the synthesis of chirped delay lines is described.

*INESC TEC, Faculdade de Engenharia, Universidade do Porto, Portugal, e-mail: mario@fe.up.pt.

†INESC TEC, Faculdade de Engenharia, Universidade do Porto, Portugal, e-mail: h.salgado@ieee.org.

‡Instituto de Telecomunicacoes, Universidade de Aveiro, Portugal, e-mail: jrp@ua.pt.

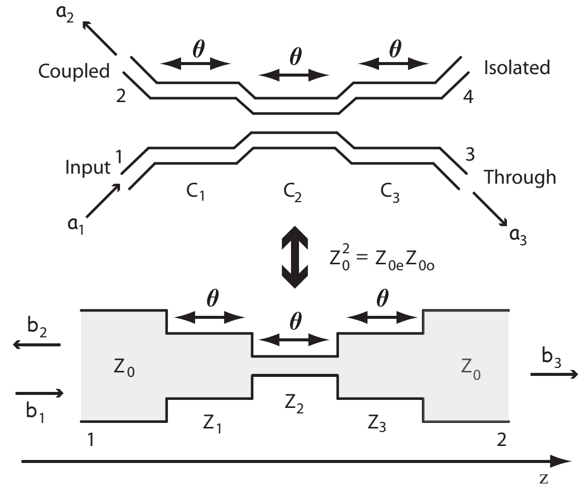

Figure 1: Equivalence Principle of TEM-mode Directional Couplers and Nonuniform Transmission Lines.

The analogy between stepped impedance transformers (or NTL filters) and cascaded directional couplers described by Young is the key idea to the work presented in this paper as it allows us to extend the use of inverse scattering and all of its advantages to the synthesis of nonuniform TEM-mode directional couplers. In this paper we describe the procedure for the synthesis of nonuniform directional couplers using inverse scattering, based on the microwave filter synthesis method reported in [3, 4]. We also address the limitations of the procedure, namely synthesis level limitations, such as the feasibility of the prototype NTL filter as a nonuniform directional coupler, and also implementation constraints concerned with the fabrication of couplers in inhomogeneous media such as microstrip.

2 EQUIVALENCE PRINCIPLE

The configuration of directional couplers consists on two transmission lines parallel to each other and in close proximity. Since the lines are very close to

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one another, the electromagnetic fields of the wave traveling on one line induces a current on the other. This is how the coupling phenomena takes place. Hence, the overall electromagnetic field configuration along coupled lines is made by a linear combination of two different propagation modes. These modes are both TEM-modes and are usually referred to as the even-mode and the odd-mode respectively [5].

Figure 1 illustrates the equivalence principle reported by Young that relates TEM-mode directional couplers and nonuniform transmission lines. The top structure in Figure 1 is a 3-section nonuniform coupler and the bottom one is the corresponding NTL prototype. Provided that all four ports of the coupler are terminated with lines of characteristic impedance Z_0 and that both the even-mode impedance Z_{0e} and the odd-mode impedance Z_{0o} satisfy the condition

$$Z_0^2 = Z_{0e} Z_{0o}, \qquad (1)$$

the equivalence principle states that the characteristic impedance profile $Z(z)$ of the prototype NTL is equal to the even-mode impedance profile $Z_{0e}(z)$ of the corresponding nonuniform coupler. Under these conditions, the return loss of the NTL prototype is equal both in magnitude and phase to the coupled-arm response of the coupler

$$S_{11_{NTL}} = \frac{b_2}{b_1} = S_{21_{Coup}} = \frac{a_2}{a_1}, \qquad (2)$$

also the insertion loss of the NTL is equal to the through-arm response of the coupler

$$S_{21_{NTL}} = \frac{b_3}{b_1} = S_{31_{Coup}} = \frac{a_3}{a_1}. \qquad (3)$$

The equalities in equations (2) and (3) show that any method suitable for the synthesis and design of NTL filters is also applicable to the design and synthesis of nonuniform couplers, provided that TEM-mode operation is considered in both prototype NTL and coupler.

Regarding to Figure 1, the relation between the coupling coefficients along the coupler structure and the even- and odd-mode impedances is given by [5]

$$C_i = \frac{Z_{0e}^i - Z_{0o}^i}{Z_{0e}^i + Z_{0o}^i}, \qquad (4)$$

where C_i, Z_{0e}^i and Z_{0o}^i are the coupling coefficient and the even- and odd-mode impedances for each section of the coupler (3 sections in the case of Figure 1). Rearranging equation (1) and substituting it into equation (4) we get

$$C_i = \frac{(Z_{0e}^i)^2 - Z_0^2}{(Z_{0e}^i)^2 + Z_0^2}. \qquad (5)$$

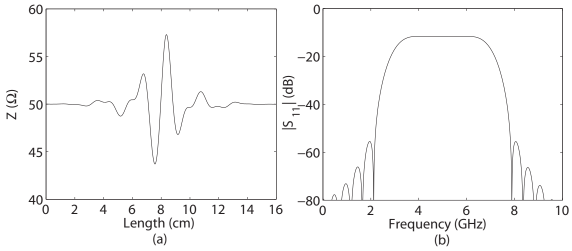

Figure 2: NTL Prototype Filter.

Applying the equivalence principle to (5) we obtain

$$C_i = \frac{Z_i^2 - Z_0^2}{Z_i^2 + Z_0^2}, \qquad (6)$$

where Z_i represents the impedance of each section of the prototype NTL. Equation (6) gives us the relation between the coupling coefficients along the coupler and the impedances along the prototype NTL filter.

3 COUPLER SYNTHESIS

In order to demonstrate the potential and versatility of the synthesis method, we next describe the procedure to synthesize a 13 dB coupler with a 5 GHz center frequency a 3 dB bandwidth of approximately 3.5 GHz and a constant group delay (dispersionless coupler) within the coupling band.

The first step in the synthesis procedure is to design the prototype NTL filter. For that, we use inverse scattering theory. The synthesis procedure for NTL filters is based on an iterative algorithm called "discrete layer peeling algorithm", described in detail in [3, 4].

Figure 2(a) shows the impedance profile of the prototype filter returned by the layer peeling algorithm whereas Figure 2(b) depicts the corresponding reflective frequency response. Note that unlike Figure 1 where the NTL prototype filter is composed by discrete impedance steps, we now have a continuous impedance profile prototype filter. The equivalence principle is still valid in this case, the only difference is that the corresponding coupler will not have a finite number of sections with constant coupling like the one in Figure 1 but will have a continuous coupling profile instead:

$$C(z) = \frac{Z^2(z) - Z_0^2}{Z^2(z) + Z_0^2}, \qquad (7)$$

where $Z_0 = 50\,\Omega$ and $Z(z)$ is the impedance profile of the prototype filter. From equation (7) we can see that if $Z(z)$ is lower than Z_0 we will get negative coupling values which are not physically

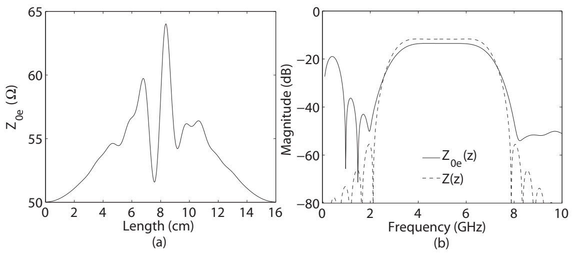

Figure 3: Nonuniform Coupler.

feasible. In order to obtain a positive set of coupling values along the length of the coupler, the values of $Z(z)$ must be made higher or equal to Z_0. One way of achieving this, with minimum impact on the desired frequency response, is to add a *window* type function to the impedance profile of the prototype filter $Z(z)$. The new impedance profile, that we may now refer to as the even-mode impedance profile, is given by

$$Z_{0e}(z) = Z(z) + W(z), \tag{8}$$

where $W(z)$ is the windowing function. If the window function were to be a constant value, it would suffice to guarantee the feasibility of the coupler provided it was large enough. However, both at the beginning as well as at the end of the coupler, the even-mode impedance would be higher than Z_0 and so the coupler would not be matched, therefore the desired frequency response would be severely compromised. Because the minimum value of $Z(z)$ occurs approximately at the middle of the coupler, a hamming window was used as the window function, resulting in the impedance profile of Figure 3(a).

Figure 3(b) compares the frequency response of the designed even-mode impedance profile with that of the NTL prototype. It is easily seen that a high coupling value band of roughly −20dB appears at around 0.5 GHz. Also the windowing process reduced the in-band coupling by around 2.5 dB and the roll-off rate has also been slightly reduced.

4 CONSTRUCTION PROCEDURE

The most logical and easy way to implement the coupler would be in microstrip due to the cheap and rather simple construction procedure. However, due to the fact that microstrip lines are inhomogeneous, the propagation velocities of the even- and odd-mode are different, resulting in a significant distortion of the frequency response. Therefore, we chose to implement the coupler in stripline technology. The prototype coupler was implemented in a

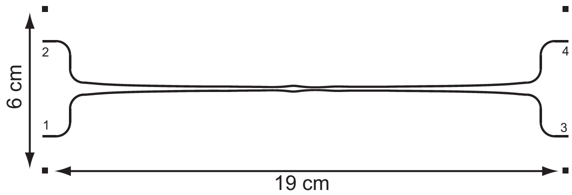

Figure 4: Coupler layout

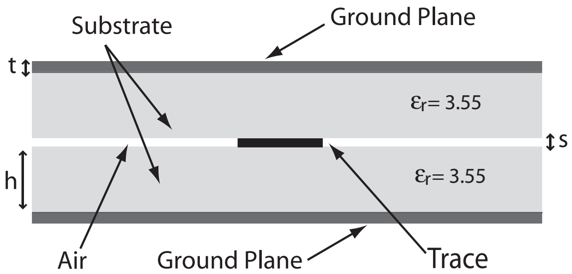

Figure 5: Stripline Configuration.

Rogers Duroid RO4003, with a dielectric constant of 3.55 and a thickness of $h = 0.813$mm. The physical dimensions of the coupler stripline (line width and spacing) were obtained by inserting the values of Z_{0e} calculated in the previous section and assuming a characteristic impedance of $Z_0 = 50\,\Omega$ in the ADS Linecalc application. The stripline conductor layout is displayed in Figure 4.

The fabrication process followed that of microstrip technology, but to achieve a stripline configuration another slab of substrate with the corresponding ground plane was added on top of the microstrip strucute, just like it is illustrated in figure 5. Furthermore, via-holes are placed along the contour of the coupler structure in order to provide a proper connection between the two stripline ground planes and to minimize the air gap between the two slabs. In Figure 6 a picture of the slab containing the stripline (the trace) is shown, where the via-holes are clearly visible.

5 RESULTS

Up until now only theoretical simulations have been shown. These simulation were performed in matlab enviroment. The method used to perform these simulations is the same as the one described in [3]. Notice that all the theoretical analysis performed in the previous sections was done considering TEM-mode propagation in a medium with effective dielectric permittivity of 3.55. We now present electromagnetic (EM) simulation results as well as measurement results. The electromagnetic simulations were carried out in Agilent ADS using

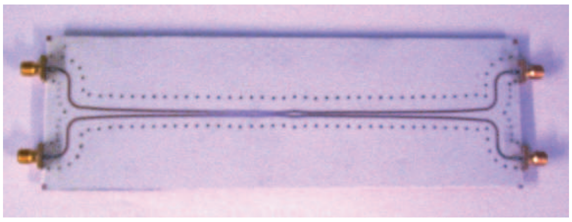

Figure 6: Fabricated Prototype Without Top Substrate Slab.

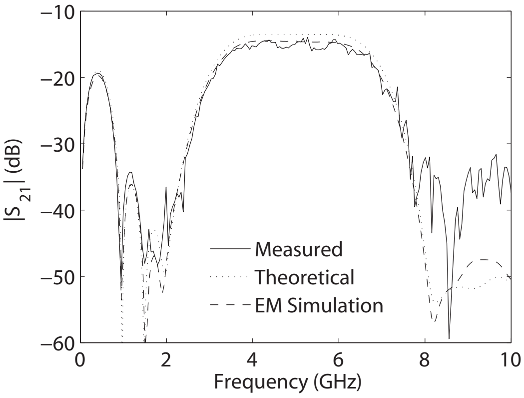

Figure 7: Coupled-Arm Frequency Response.

the method of moments. In Figure 7 both theoretical and EM simulation results are presented for the magnitude of the coupled arm response $|S_{21}|$ and compared with the measurements. The theoretical and EM simulation results match very well, except for a small difference in amplitude in the coupling band. We hold the substrate losses of the substrate accountable for this difference since no losses were considered in the theoretical simulations. Concerning the measured response, we clearly see an excellent agreement with the theoretical and EM simulation results. Figure 8 compares the results for the group delay of the coupled-arm response. In the coupling band, both experimental measurement and EM simulation results are in good agreement. The theoretical value of the group delay, however, is slightly lower than the measured one because the extra length of stripline on all ports necessary to accommodate the SMA connectors was not taken into account in this simulation.

6 CONCLUSIONS

We have successfully synthesized a wide-band dispersionless coupler using inverse scattering theory and managed to fabricate it in a quasi-stripline configuration. The use of the inverse scattering method assures that any frequency response can

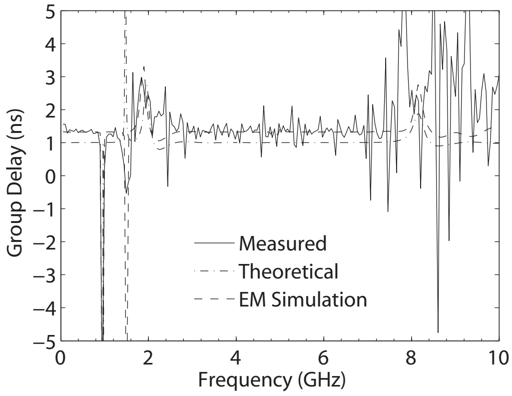

Figure 8: Coupled-Arm Group Delay Response.

be achieved, as long as the prototype NTL filter is feasible. The measurement results are in good agreement with both theoretical and EM simulations, however, a stripline high quality industrial-class fabrication process would naturally improve the experimental results.

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