CHAPTER 1. INTRODUCTION

1.1. Historical Background

Differential phase shifters have application in various microwave systems, for example in hybrid circuits and wide band phased-array antennas. Differential phase shifters are four-port networks providing constant differential phase shift across their two output ports. During the last 35 years phase shifters comprising coupled lines proved to exhibit the greatest bandwidth [1].

Wideband phase shifting networks suitable for application at low frequencies were widely investigated during the period 1946-1953 [2,3,4,5,6,7]. In 1956 Jones and Bolljahn [8] published an equation for the phase shift through a single C-section of coupled lines. Cohn [9] first suggested the use of the coupled-line all-pass network in broadband phase-shift networks in 1955, which led to the work of Schiffman in 1958 [10].

The basic Schiffman phase shifter, shown in Figure 1, consists of two separate TEM transmission lines, one of which is a length of uncoupled line called the reference line. The other line is a single C-section, consisting of a pair of parallel coupled transmission lines directly connected to each other at one end. The coupled section is one quarter wavelength long at the centre frequency. Schiffman classified types A, B, C, D, E and F networks covering combined C-sections in six basic configurations. He concluded that a 5 : 1 bandwidth may be covered using these networks.

Cascaded all-pass networks, also known as microwave C-sections, have been analysed by Steenart [11] in 1963 and Zysman and Matsumoto [12] in 1965. Crystal [13] solved the analysis problem and exact synthesis of cascaded C-sections in 1966, using matrix methods and Richard's Theorem [14], but restricted the various coupled sections to having equal lengths. Shortly afterward Schiffman derived analysis equations for multi-section phase shifters (see Figure 2) with any amount of coupled sections, also including unequal lengths [15], as shown in Figure 2. Late in 1966 Shelton and Mosko [16] described an approximate iterative synthesis technique for multiple-section Schiffman phase shifters and tabulated the results.

In 1968 Tresselt published a design procedure for a continuously-tapered coupled-section phase shifter [17]. He realised the important fact that the spread in coupling values between adjacent sections is large enough to produce significant reactive discontinuities in practical TEM line geometries, adversely affecting VSWR and phase accuracy of stepped devices at high frequency.

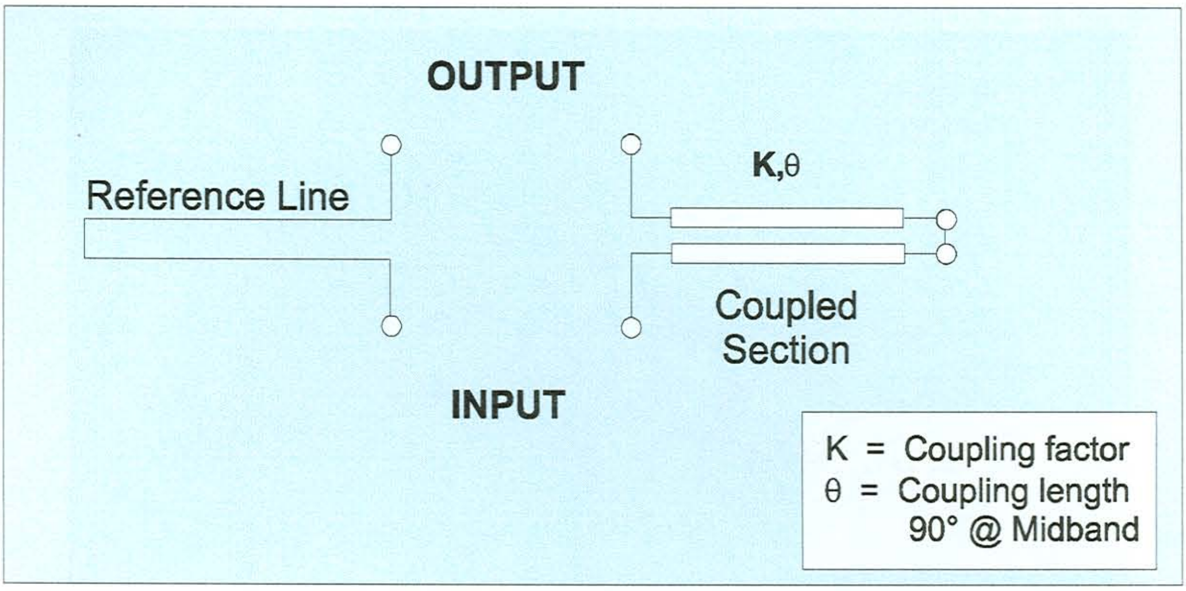

Figure 1 : The basic Schiffman phase shifter

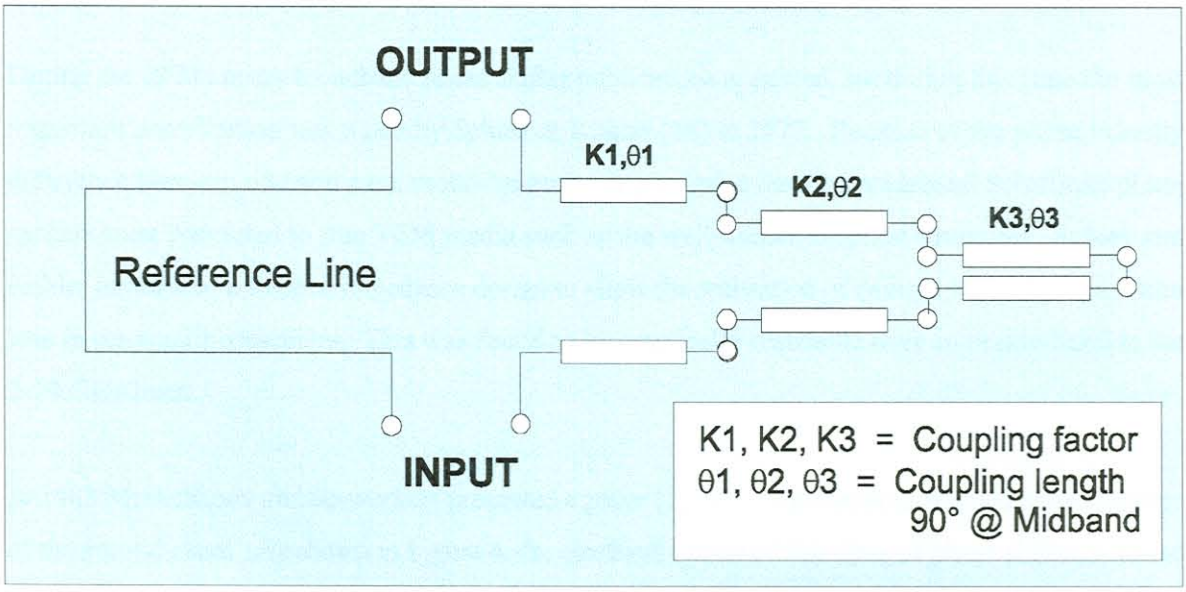

Figure 2 : Multi-section Schiffman phase shifter

His continuously tapered synthesis procedure considerably reduced the impact of these effects. Such a tapered-line phase shifter is shown in Figure 3. He then designed and constructed such a device over a 10 : 1 band. The results however showed that the parasitic effects due to the intra-connecting strap limited the upper frequency band and could only be partially compensated for, limiting the device application to about 9 GHz.

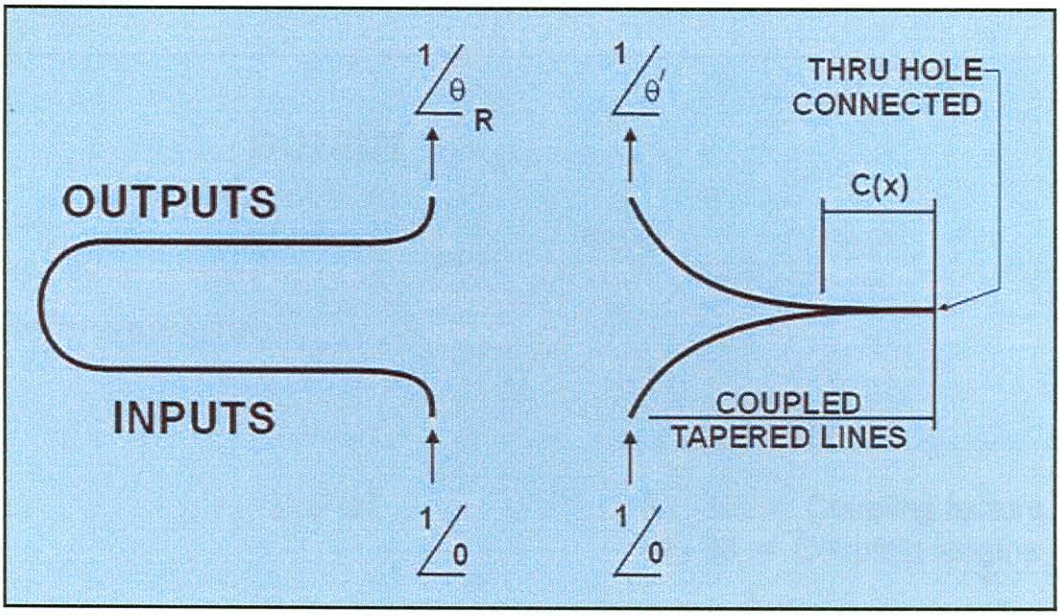

Figure 3 : Tapered line phase shifter

During the 1970's many broadband phase shifter publications appeared, but during this time the most important contribution was made by Schiek & Köhler [18] in 1977. Because of the phase velocity difference between odd and even modes in microstrip coupled devices, wideband Schiffman phase shifters were restricted to true TEM media such as the well-known stripline structures. Schiek and Köhler introduced a stepped impedance design to allow the realisation of devices with very low return loss in microstrip structures. This was found to be practically realisable over an octave band in the 2-10 GHz band.

In 1983 Meshchanov and co-workers presented a paper [1] on the synthesis of stepped phase shifters of the second class. As shown in Figure 4, the electrical circuit of this class of phase shifter is based on the cascaded connection of alternating sections of coupled and uncoupled lines of different electrical length in contrast with phase shifters of class I which have only coupled sections. They published solution tables for a number of optimal designs. The advantages of class II phase shifters over the classical class I phase shifters were demonstrated in several publications [19, 20, 21]. However, class II phase shifters have a higher ripple value per optimized bandwidth and, due to the very high coupling ratio of adjacent sections, severe parasitic effects at the transitions. This limits the practical upper frequency of operation. The coupling values of class II phase shifters are on average

4% lower than class I networks, and the structure is also smaller. It was also noted that by making the coupling coefficients equal, the design is significantly simplified.

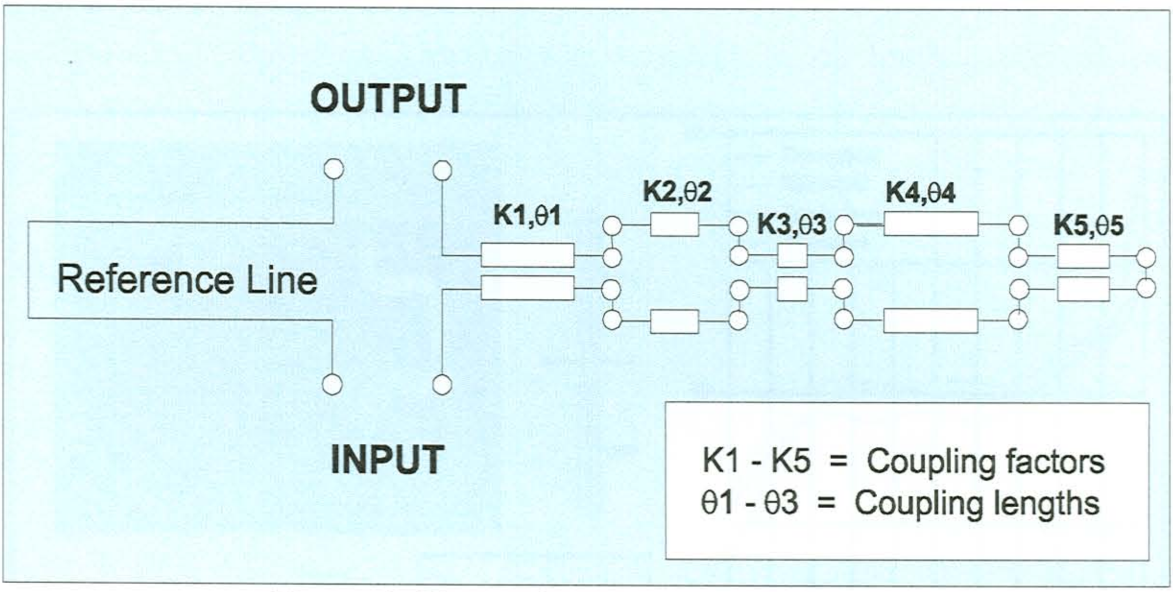

Figure 4 : Five-section phase shifter of class II

Equations for the synthesis of single-section Schiffman phase shifters were also presented in 1985 by Quirarte and Starski [22]. The equations enable the calculation of the bandwidth and phase ripple for a given coupling coefficient, or the coupling coefficient of the section for a given phase deviation and bandwidth.

In order to achieve larger bandwidth, it is necessary to use sections which are more tightly coupled. This is difficult to realise. In a paper titled "Novel Schiffman Phase Shifters", Quirarte and Starski [23] showed in 1993 how parallel-connected coupled sections of loosely coupled lines can obtain the same differential phase shift as a single tightly coupled section. This is shown in Figure 5. Another advantage is that the parallel section has approximately double the impedance of conventional sections. This reduces parasitic components at transitions and increases the coupling factor.

In 1994 Meschanov et al [24] published an article called " A new structure of microwave ultra-wideband differential phase shifter". Optimized designs of this new structure were tabulated, which is merely a Schiffman phase shifter of type C [15]. The type C network has a 6 : 1 bandwidth for a 1.2° ripple. It was concluded that the optimum type C network has a maximum coupling coefficient for the shortest section and a minimum coupling coefficient for the longest section. According to the paper, a smaller phase ripple was achieved than for other stepped types, allowing wider bandwidth for the same ripple. The coupling values were found to be lower than other types. The disadvantage is that the structure is larger than other types.

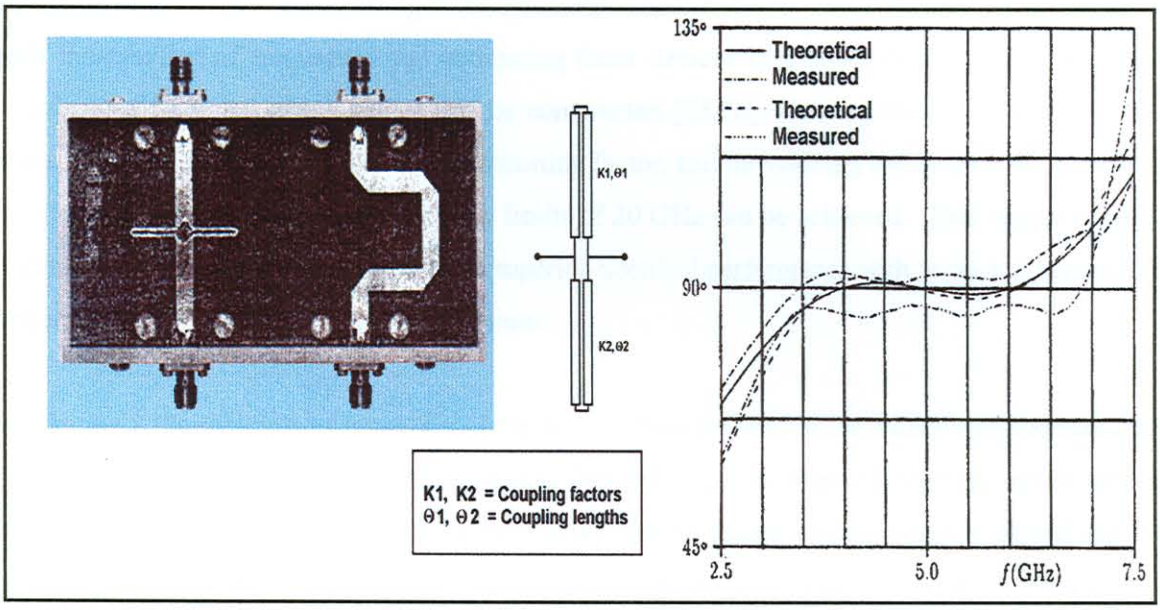

Figure 5 : Parallel-connected Schiffman sections with theoretical & measured results

From this study it was clear that virtually all work regarding wideband differential phase shifters was based on Schiffman's original work. No significant progress has been made except for some improvements on, or extensions of the classical Schiffman phase shifter.

1.2. Existing Shortcomings in Differential Phase Shifter Design

Up to the present a set of design rules linking size, coupling, structure type and class to realise the optimal ultra-wideband phase shifter has not yet been formulated. There has been no successful design or results published for a 2-18 GHz equi-ripple device. Only one researcher [17] notes that for ultra-wideband operation, it is essential to avoid section step transitions which cannot easily be accounted for in the mathematical model. This is an important fact that will be discussed in Section 3.3 in detail. The band limiting obstacle that could not be overcome was the interconnecting discontinuity at the far end of the coupled lines.

1.3. Contributions of this Thesis

It will be shown that all of these problems can be overcome by approaching the problem from an entirely different angle. By realising that a symmetric coupler has the unique property of quadrature split independent of frequency, and combining these devices in a novel configuration, an ultra-wideband differential phase shifter can be constructed [25,26]. Noting that the transitions and manufacturing tolerance will be the band limiting factor, and introducing the concept of symmetry to alleviate these effects, upper frequency limits of 20 GHz can be achieved. This unique class of microwave differential phase shifter offers superior electrical performance with respect to bandwidth, upper frequency limit, size and synthesis time.

In Chapter 2 the principle of operation of the novel ultra-wideband phase shifter will be presented. The coupler-based phase shifter and the classical Tresselt's tapered coupled-line phase shifter will be compared. In Chapter 3 the three main elements of the phase shifter are thoroughly analysed and the synthesis of each is discussed. Considerable attention is given to the unique semi-distributed splitter required to excite the coupler on both sides of the triplate centre substrate [27]. An in-depth sensitivity analysis is presented in Chapter 4 to provide insight into the sensitivity of the phase shifter's performance to manufacturing tolerances. General phase shifter synthesis guidelines are presented in Chapter 5, and processes and tolerance requirements are discussed. A typical ultra-wideband phase shifter is then synthesized and the theoretical and practical results are presented. The example is specifically chosen to be a 45° phase shifter, as the sensitivity analysis indicated this case to be the most sensitive to manufacturing tolerances. The document ends with a summary and general conclusions. All work presented in this thesis is the authors own, unless specified by means of reference.

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