CHAPTER 3

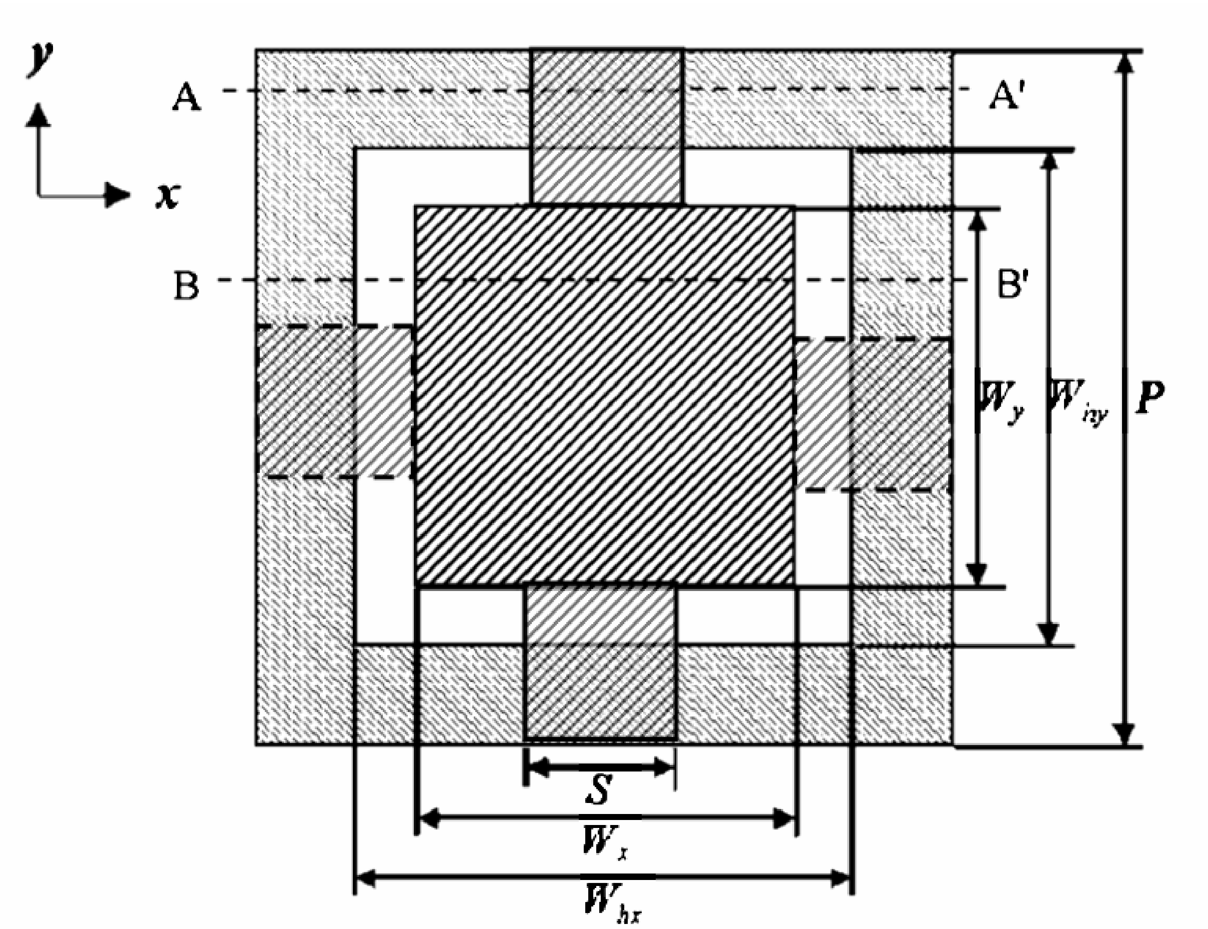
Design and Application of Synthetic Quasi-TEM Mode Transmission Lines

3.1 Operational Principle of Meander Complementary Conducting Strips (CCSs)

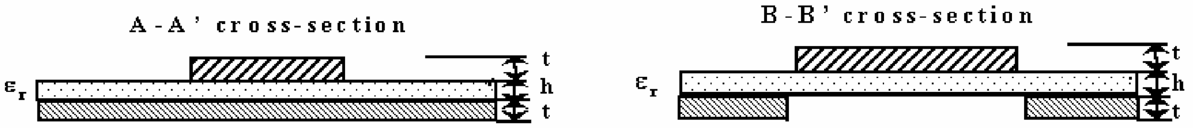
This section qualitatively describes the principle of operation of the synthetic TL proposed by this study, which is particularly suitable for the syntheses of quasi-TEM TLs of a broader characteristic impedance range than that of the conventional MS to carry on high-performance microwave passive circuit designs. The proposed guiding structures are made on multilayered substrates such as PCBs, LTCCs, and MMICs like RF CMOS and GaAs pseudomorphic high electron-mobility transistor (pHEMT) processes. Following the experiences of designing a broad range of miniaturized microwave integrated circuits using the proposed TL structures, this dissertation presents the basic design concepts, guiding characteristics, and some important application examples for illuminating the ideas of making a fundamentally 2-D quasi-TEM guiding structure that offers an additional one degree of freedom for making controlled impedance lines to meet design needs.

3.1.1 Proposed Concept of Quasi-TEM Synthetic TL

The proposed quasi-TEM TL is a one-dimensional periodical structure meandered in a 2-D plane. A typical unit cell, shown in Fig. 3.1(a), has dimensions much smaller than the operating wavelength (λ_g), usually 20 cells in a quarter-wavelength line. In the unit cell of Fig. 3.1, the top metal layer consists of a patch with four connecting arms for four-way interconnects, in which at least two arms are employed for connections of cells. At the bottom of the unit cell is the mesh ground plane structure, which forms a 2-D periodical structure for the ground plane of the proposed guiding structure. Consider a square periodical structure with a periodicity of P. The guiding structure integrates two TLs in a single cell by drawing A-A’ and B-B’ cuts horizontally across the unit cell. The left column of Fig. 3.1(b) displays a cross-sectional view of the unit cell along the A-A’ cut for hybrid PCB/MMIC and lower Si or GaAs substrate without. The left-hand-side column clearly shows that the well-known MS structure is independent of the passivation in the MMIC process. The right-hand-side column in Fig. 3.1(b), however, presents a MS with the tuning septa [52] or, equivalently, an elevated CPW [53] across the B-B’ cut of the unit cell. Varying the width of the patch W_x (W_y) and the inner hole dimension of the mesh W_{hx} (W_{hy}), the high-to-low characteristic impedance ratio of 10.1 had been reported for the MS with the tuning septa [52]. On the other hand, the practical



(a) Two-dimensional (2-D) top view



(b) Cross-sectional view for the MIC

Fig. 3.1. Geometries of the CCS unit cell. (a) 2-D top view, (b) Cross-sectional view.

range of tuning the characteristic impedance of a conventional MS by varying the width S is typically much less than that of the MS with the tuning septa, say 8.0. As the guided electromagnetic wave traverse the unit cells, it experiences the alternating types of guiding structures of different characteristic impedance levels in distances far less than the equivalent wavelength of the resultant TL. Since an MS with and without the tuning septa support the quasi-TEM mode and discontinuities inherent in the unit cell are comparably small against the equivalent wavelength, the combined guiding structure of the unit cell also supports the quasi-TEM mode by merging two types of guiding structures. In other words, electrical fields emanating from the positive charges on a top signal trace should always find the shortest path to terminate at the bottom conductive strips in a very similar manner as those of an MS with and without the tuning septa, thus rendering the quasi-TEM mode, provided the dimension P of the unit cell is much smaller than the operating wavelength. In this case, the discontinuities associated with the proposed guiding structure will not cause significant radiation losses or stopband characteristics frequently typically observed in the periodical structures. This dissertation, however, focuses only on the quasi-TEM propagation characteristics of the CCS MS in the lower frequency region, where many useful applications are desirable.

The patch of dimensions W_x by W_y and the mesh ground plane with hole of dimensions W_{hx} by W_{hy} form complementary surfaces, therefore we call the proposed TL the CCS TL. The upper metallic patch surface is connected to the adjacent cells by connecting arms, which form a relatively small overlapping area to both top and bottom surfaces and slightly perturb the complementary surfaces.

In Section 3.2, we will demonstrate that, given the same periodicity P and the fabrication process, various CCS TLs can be synthesized to yield the same characteristic impedance. Such a unique property of the CCS TL is a manifestation of the fact that the proposed quasi-TEM guiding structure is a 2-D structure in view of its periodical variations along the propagating direction while maintaining the same substrate geometry, thus supporting an additional degree of freedom for designing TLs.

3.1.2 Compacted Passive Circuits Using CCS TLs

The most important feature of the proposed CCS TL is its application for designing compacted TL passive circuits such as the one shown in Fig. 3.2, which is a photograph of the experimental 5.4-GHz rat-race hybrids designed by employing conventional MS and the CCS TL, respectively, to achieving nearly the same four-port network parameters. Both designs are printed simultaneously on a Roger RO-4003 0.203-mm substrate of relative dielectric constant ε_r equal to 3.38. One immediately recognizes that the compacted rat-race hybrid based on the CCS TLs occupies much less area than the familiar ring-shaped design using a conventional MS, which wastes a substantial area by over 80%. Section 3.2 will show why the CCS TL is much better than MS in guided-wave propagation characteristics for compacted meandered microwave passive circuit designs. Here, we report the basics necessary for an accurate assessment of area size and make a comparison between the designs using the conventional MSs and CCS TLs before entering the serious design phase. Given the case study of the 5.4-GHz four-port rat-race hybrid, a total wavelength of 6/4 λ_g is required for both designs using MSs and CCS TLs. In the typical ring-shaped configuration of a rat-race hybrid based MS, the circumference of the ring is

$$\left(\frac{6}{4}\right)\lambda_{g1} = 2\pi R_1 \ . \tag{3.1}$$

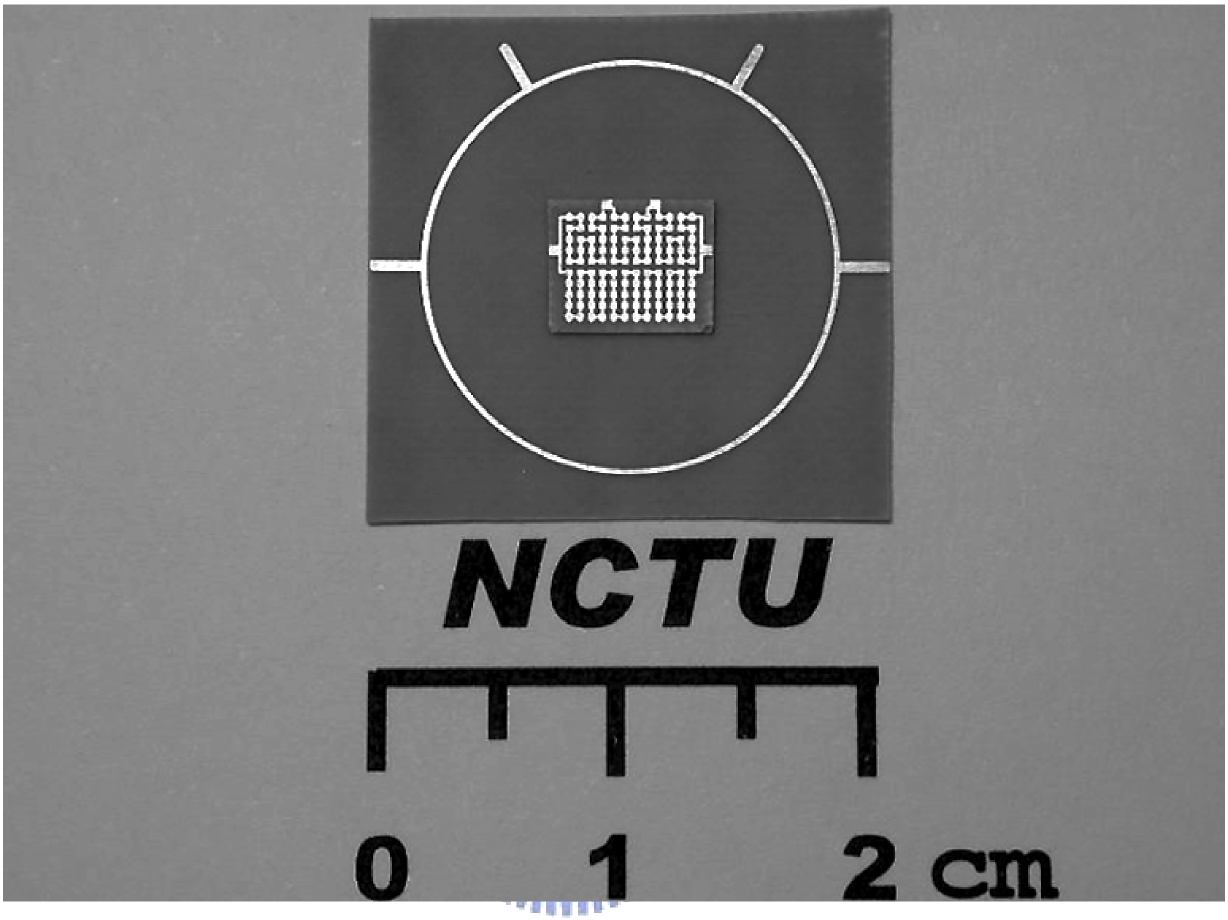


Fig. 3.2. Comparison of mask patterns of the 2-D guided structures of the CCS rat-race hybrid prototype (inside pattern) and the traditional MS rat-race hybrid (outside pattern).

where R_1 is the radius of the ring and λ_{g1} is the guided wavelength of the conventional 70-Ω MS line at the operating frequency f_o. Excluding the T-junctions required for the four-port interface, the estimated area of an MS rat-race hybrid (A_1) is

$$A_1 = \pi R_1^2 = (\frac{9}{16\pi})\lambda_{g1}^2 \ . \tag{3.2}$$

The CCS TL realization of microwave passive circuits adopts an entirely different philosophy by placing the meandered CCS TLs in a compacted 2-D plane in an array shape by simply connecting the connecting arms of the cells along the desired directions of propagation. Thus, the total area (A_2) required to accomplishing the design example of the rat-race hybrid is

$$A_2 = (\frac{6}{4})\lambda_{g2} \cdot P \ . \tag{3.3}$$

To this end, an ARF of the particular case study can be expressed by

$$ARF = 1 - \frac{A_2}{A_1} = 1 - \frac{(\frac{8\pi}{3})(\frac{P}{\lambda_o})(SWF_{MS})^2}{SWF_{CCS\ TL}} \ . \tag{3.4}$$

where SWFs of the MS and CCS TL are, respectively, defined as $SWF_{MS} = \lambda_o/\lambda_{g1}$, $SWF_{CCS\ TL} = \lambda_o/\lambda_{g2}$, and λ_o is the guided wavelength in free space at the operating frequency f_o. Equation (3.4) shows a linear dependence of the ARF against the periodicity P of the CCS TLs. The smaller the value of P will result in a larger ARF, which is a figure-of-merit to demonstrate the important area of CCS TLs in the process of designing compacted microwave circuits. The proper choice of P for making CCS TLs depends upon the following three factors:

1) required range of the characteristic impedances of the TL;
2) minimum linewidth and line spacing of the particular integrated-circuit process;
3) maximum current handling capability of the CCS TL.

Quick estimation by assuming that $SWF_{MS} = SWF_{CCS\ TL} = 1.5$, $P = 500\ \mu m$, and $f_0 = 5.4$ GHz, the ARF will be 88.7%, which is very close to detailed analyses and experimental results to be discussed.