CHAPTER 1

Background

Transmission line (TL) can be synthesized by different substrate materials and/or metal strips in mixed configurations. Therefore it can be realized by different manufacturing techniques. And these combinations could produce various synthetic TL structures that exhibit marvelous propagation characteristics and suit for compact microwave integrated circuits (MICs), antennas and other devices. The research and development of the synthetic TL is a key factor to miniaturized MICs and scanning antennas.

This dissertation investigates both a new synthetic quasi-transverse elctromagnetic (Quasi-TEM, EH_0) line for compact microwave integrated circuit (MIC) and a novel synthetic first higher-order (EH_1) leaky line for compact beam-steering antenna. The background for these two topics will be individually described as follows.

1.1 Background and motivation of miniaturized Monolithic MIC

Here, we take an example to illustrate the benefit of the miniaturized MIC.

Figure 1.1 displays a circular wafer topology that is composed of many square chips for the MMIC. If the total available area of the wafer is A, and the chip area for the MMIC is a_1, then the yield will be equal to $(A/a_1) \times$ (1- defect density) approximately, where the defect density has relation with the maturity of the manufacturing processes. A mature manufacturing process will give a superior defect control and a lower defect density. On the same condition of defect density, as the a_1 is decreased, the yield will be increased. The cost per chip can then be reduced.

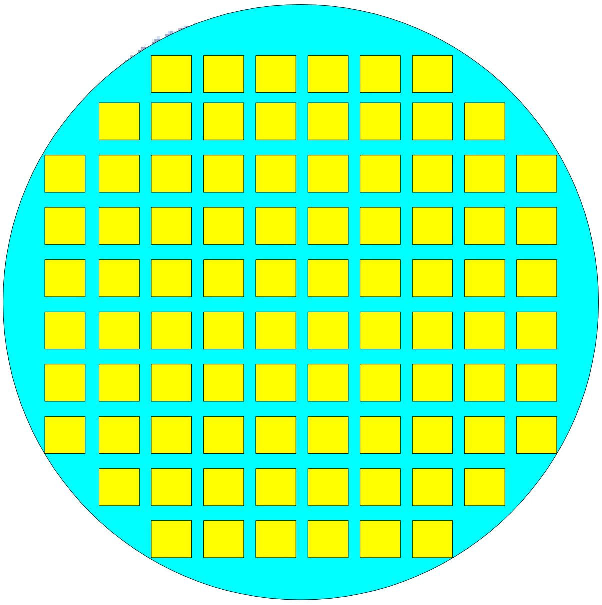


Fig. 1.1. A circular wafer topology that is composed of many square chips for the MMIC.

Hence, a miniaturized method for the MMIC that satisfies the design rule and is completely compatible with the mature manufacturing processes will be the best candidate.

In the next example, we will illustrate the general phenomenon for the MMICs and the problem for their miniaturization. Figure 1.2 shows a very low-conversion-loss wideband monolithic microwave integrated circuit (MMIC) subharmonic pumped (SHP) diode mixer with size of 1.5 mm × 2.0 mm [1]. If we observe the layout topology of the MIC, it can be found that many of the distributed elements, such as filters of various specifications, inductors, and matching networks are used for the MMIC. These passive components require much larger chip area than the active devices. Therefore, the size reduction of the distributed passive components will be the key-factor to the miniaturized MICs.

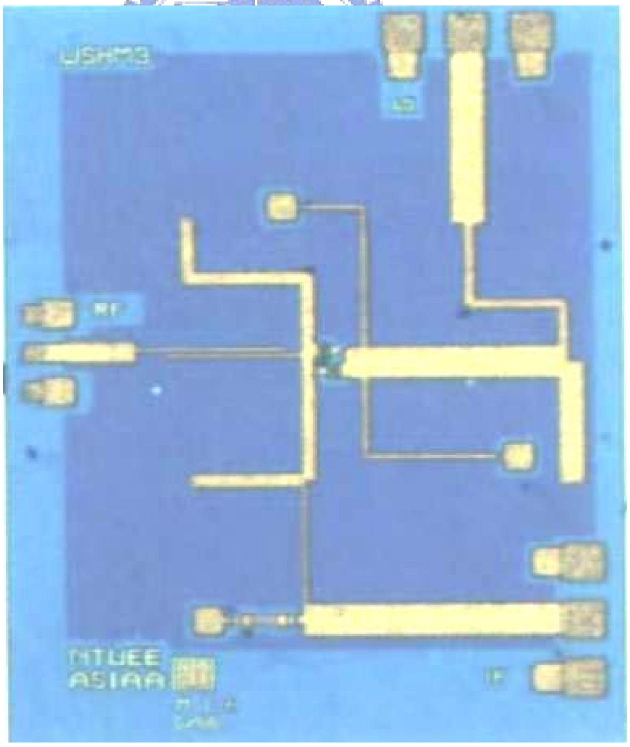


Fig. 1.2. 78–114 GHz Monolithic Subharmonically Pumped GaAs-Based HEMT Diode Mixer with size of $1.5\ mm \times 2.0\ mm$ [1].

In the following, we will show the typical miniaturized methods, the related operational principles, and their limitations. One of the most common methods for reducing dimensions is to make a microwave circuit into a monolithic integrated circuit, such as that shown in Fig. 1.3.

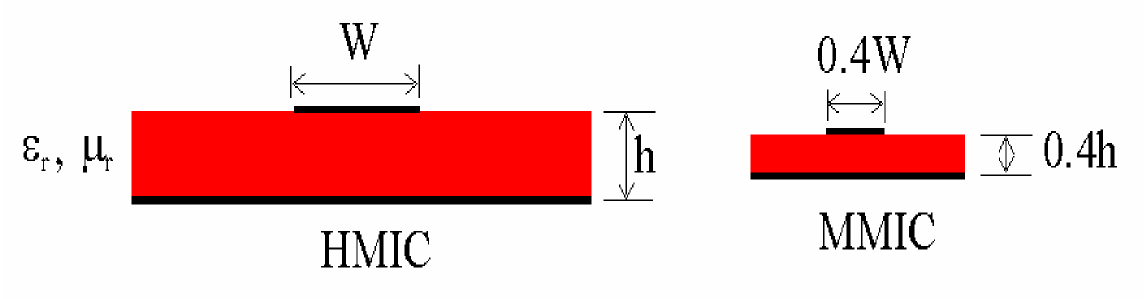


Fig. 1.3. The cross-section views of the hybrid microwave integrated circuit (HMIC) and monolithic microwave integrated circuit (MMIC).

Method 1: Scaling

The principle of scaling has been applied in the miniaturization process where the propagation constant β and the characteristic impedance Z_c for the HMIC are approximately equal to the corresponding values of β and Z_c for the MMIC if the same metal (conductivity σ) and substrate material (relative permittivity ε_r and relative permeability μ_r) are adopted. The required estimated area for the experimental MMIC is about 40 % of that for the HMIC with same electrical characteristics [2]. If the demand volume for the MIC is small, the manufacturing price utilizing the MMIC process will be much higher than that using the HMIC process.

Method 2: RFIC Miniaturization Using Lumped Elements

Lumped elements, such as helical inductor, parallel plate capacitor in the HMIC, and planar spiral inductor as in Fig. 1.4, metal-insulator-metal (MIM) capacitor in the MMIC, are used to reduce the size of the MIC [3], [4]. Because it is essential that the dimensions of a lumped element be much smaller than the wavelength of the operating frequency, the circuit area of the entire passive elements can then be substantially reduced.

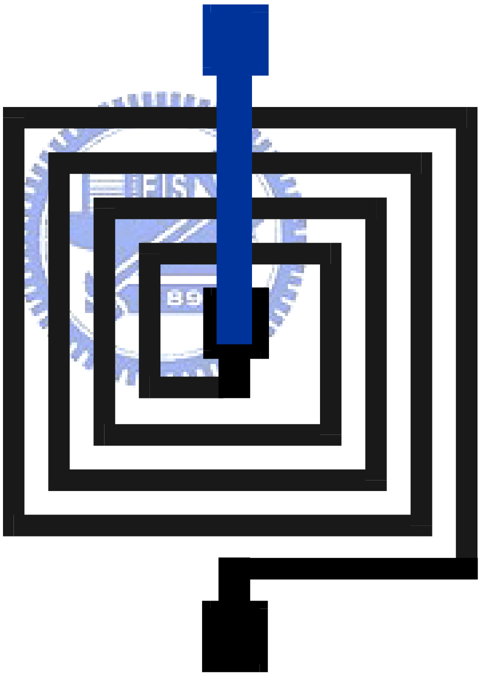


Fig. 1.4. The planar spiral inductor in the MMIC.

Since RF foundry can offer very limited choices for lumped elements, and often lacks support for scalable inductors and capacitors, accurate design of on-chip inductors and capacitors is therefore of primary importance. Another problem is the repeatability of the inductors and capacitors. The characteristics of these passive components may vary from lot to lot and wafer to wafer. As the operating frequency increases, the behavior of inductor is more distributive rather than lumped, as it was initially intended. This further complicates the MMIC design at higher microwave frequencies. Therefore, lumped elements, as compared to the waveguide elements, are generally operated at lower operating frequencies, and are rarely used for broadband and/or millimeter wave RFIC designs except the biasing circuits.

Method 3: Use of High permittivity (or Permeability) Constants Substrate

Small microwave ceramic components often employ high relative dielectric constant (ε_r) substrates. Sometimes ε_r can reach 100 [5]-[7]. The miniaturized principle is indicated in Fig. 1.5. The device dimension is typically inversely proportional to the square root of ε_r [8].

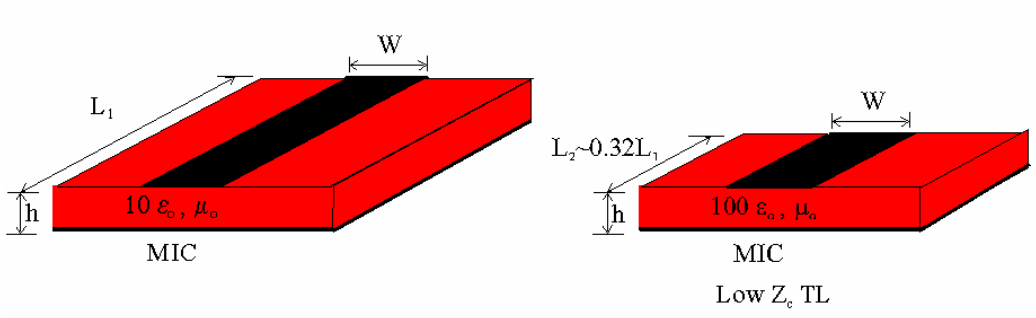


Fig. 1.5. The miniaturized TL for the high permittivity $\varepsilon_r\varepsilon_o$ substrate.

Usually, the higher ε_r the material has, the higher the loss occurs. And the low Z_c TL is easier to get than the high Z_c TL. The reason is that the high Z_c TL is made from the much reduced width TL, and this will largely increase the loss.

An alternative for miniaturization is to apply high-permeability μ_r materials instead of high ε_r materials. Usually the higher μ_r the material has, the higher the loss occurs [9], [10]. Using this alternative, the high Z_c TL is easier to obtain than the low Z_c TL, but the width of TL must be widened for the same Z_c demanded. This, however, adversely affects the efforts for making miniaturized microwave circuits.

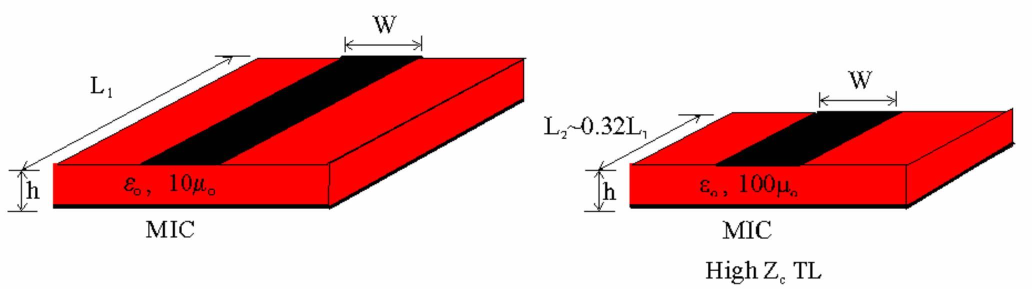


Fig. 1.6. The miniaturized TL for the high permeability $\mu_r\mu_o$ substrate.

Method 4: Slow-Wave Line

The wavelength λ_g of a slow-wave TL is much smaller than λ_0. Therefore, this kind of device can also be utilized to decrease the TL length of MICs, thus reducing the chip real estate. A typical slow-wave TL, such as the metal-insulator-semiconductor (MIS) TL, is shown in Fig. 1.7. The MIS slow-wave TL comprises of the doped region to change the distributions of the electric field and magnetic field of the microstrip (MS). This will make the slow-wave factor (SWF), λ_0/λ_g, significantly increased [11], [12].

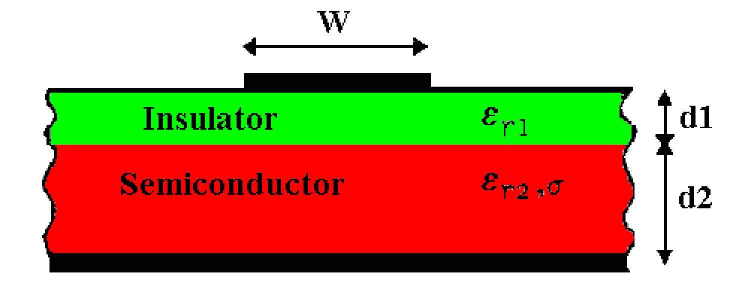


Fig. 1.7. The cross-sections view for the MIS slow-wave TL.

The SWF of a MIS TL will be decreased as the frequency is increased, since the imaginary part of the permittivity responsible for spatial separation of electric and magnetic energy storage is inversely proportional to the frequency ($\varepsilon'' = \sigma / \omega\varepsilon_o$). Other problems of the MIS TL are its low characteristic impedance and large dielectric loss. This prohibits extensive applications of the MIS slow-wave lines.

For the typical miniaturized methods mentioned above, the structural and material parameters, such as the substrate thickness and substrate properties (higher μ_r, higher ε_r, and different σ), must be changed and/or adjusted for making the reduced size MICs. Both structural and material parameters are defined once the foundry process is chosen, and the process alteration or tuning is most of time prohibited for the mature manufacturing process since it is provided by the foundry process provider for general use.

To develop a miniaturized method that is fully compatible with the existing mature fabrication process, and is of no special needs for mask change or process tuning, is an important research subject for the reduced-size RFIC design.

Method 5: TL Syntheses for Larger SWF

A new slow-wave guiding structure, named the uniplanar compact photonic-bandgap (UC-PBG) MS structure, is shown in Fig. 1.8 [13]. This UC-PBG structure applies the periodical structure in the ground plane to increase the SWF of the basic MS structure.

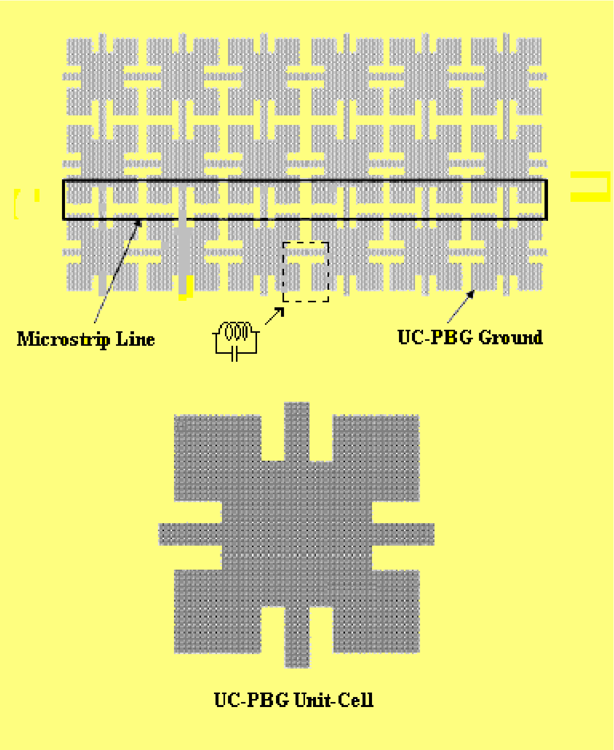


Fig. 1.8. The UC-PBG MS structures [13].

These narrow branches, together with the insets at connections, introduce additional inductance seen by the microstrip. Moreover, the gaps between neighboring pads enlarge capacitance. The series reactive elements and the shunt capacitances alter the ground plane characteristics, thus changing the propagation constant of the composite microstrip line sitting above the UC-PBG groung plane. This constant is much larger than that of a conventional MS line.

Such UC-PBG structures have been extensively applied for making smaller low-loss passive components, such as compressed low-pass filter (LPF), band-pass filter (BPF), high-gain patch antenna and TEM waveguide with intrinsic spurious and leakage suppression.

Another new slow-wave guiding structure, named the electric-magnetic-electric (EME) structure, is shown in Fig. 1.9 [14]. This EME structure applies the periodical structure in the signal line to increase the SWF of the basic MS structure. The metal strip is a sheet of composite metal made of EME surfaces. The magnetic surface is realized by the coupled and connected metallic coils. The periodic coils array forms a high-impedance state in a certain bandwidth. The EME surfaces, formed by both the electric and the magnetic surfaces, allow an additional degree of freedom to vary the propagation characteristics. The EME structure effectively offers increased SWF, higher Z_c, and low loss properties that can reduce the TL length of passive elements and at the same time make practical circuit design.

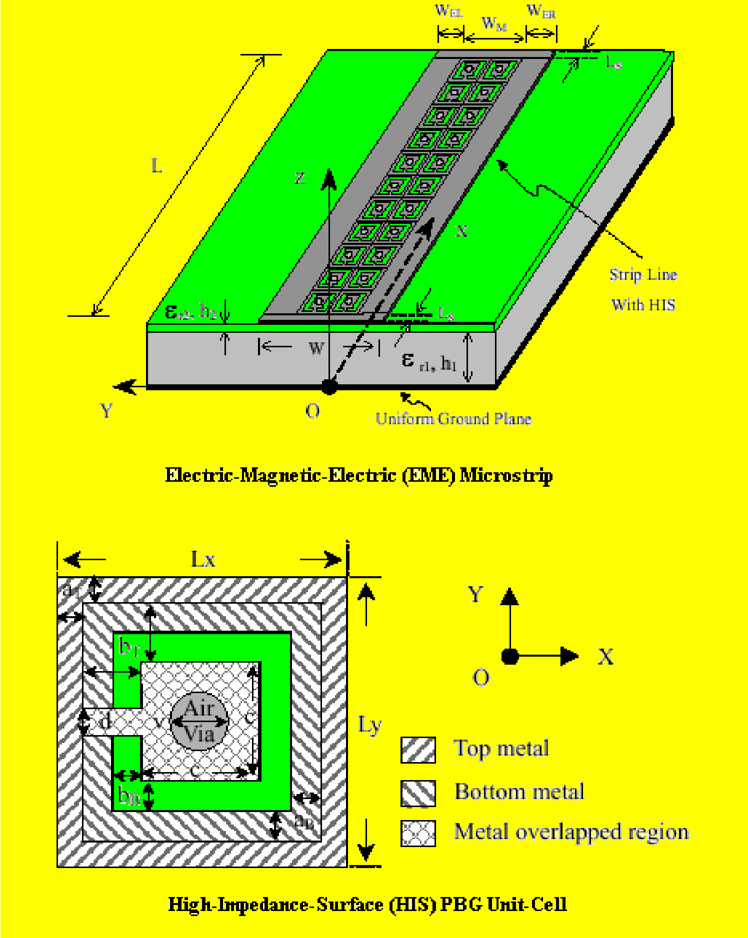
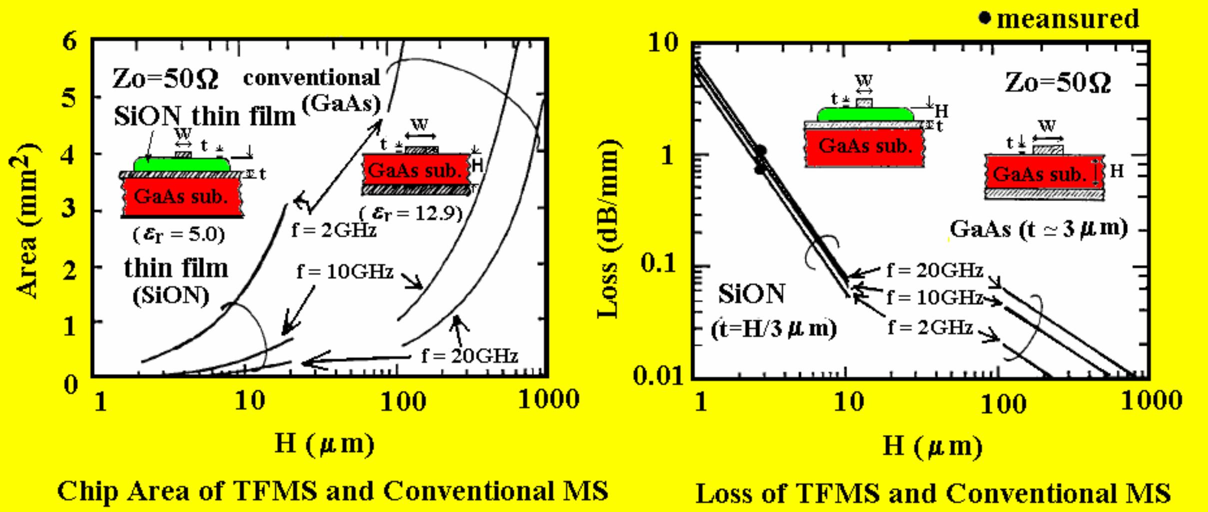


Fig. 1.9. The EME MS structures [14].

In view of the above-mentioned methods, scaling of EM devices appears the most direct way of making smaller RF device. Therefore Method 1 had been popular for miniaturized RFIC design, where thin-film microstrips (TFMSs) had been widely used [15]-[20]. This technique does not need the high-permittivity, the high-permeability materials, or the exotic periodical structures to make smaller microwave devices. But it suffers great losses during the scale-down process. A comparison on chip area and loss for both thin-film microstrip (TFMS) and conventional MS is shown in Fig. 1.10 [16].



Chip Area of TFMS and Conventional MS Loss of TFMS and Conventional MS

Fig. 1.10. Comparison on chip area and loss of TFMS and conventional MS [16]

It is shown that the chip area of TFMSs is proportional to the substrate thickness. Furthermore, the loss of the TFMSs is proportional to the surface resistivity [15] and it is drastically decreased as the thickness of the thin film is increased for the thinner substrate cases. For example, the dots in the right plot of Fig. 1.10 indicate that the measured loss for the TFMS line can be reduced by 90 percent as the SiON film thickness is increased from 3-μm to 6 μm.

To save chip area, designers often meander the TFMSs to make very compact passive components in the MMICs [15]-[18], [21], [22] and HMICs [23], [24]. A wide-band 6-18-GHz monolithic magic-T with chip size of 0.9 mm × 1.0 mm was reported [16]. In this device, two quarter-wavelength TFMSs occupy most of the chip area that is approximately 0.3 mm × 0.5 mm as shown in Fig. 1.11.

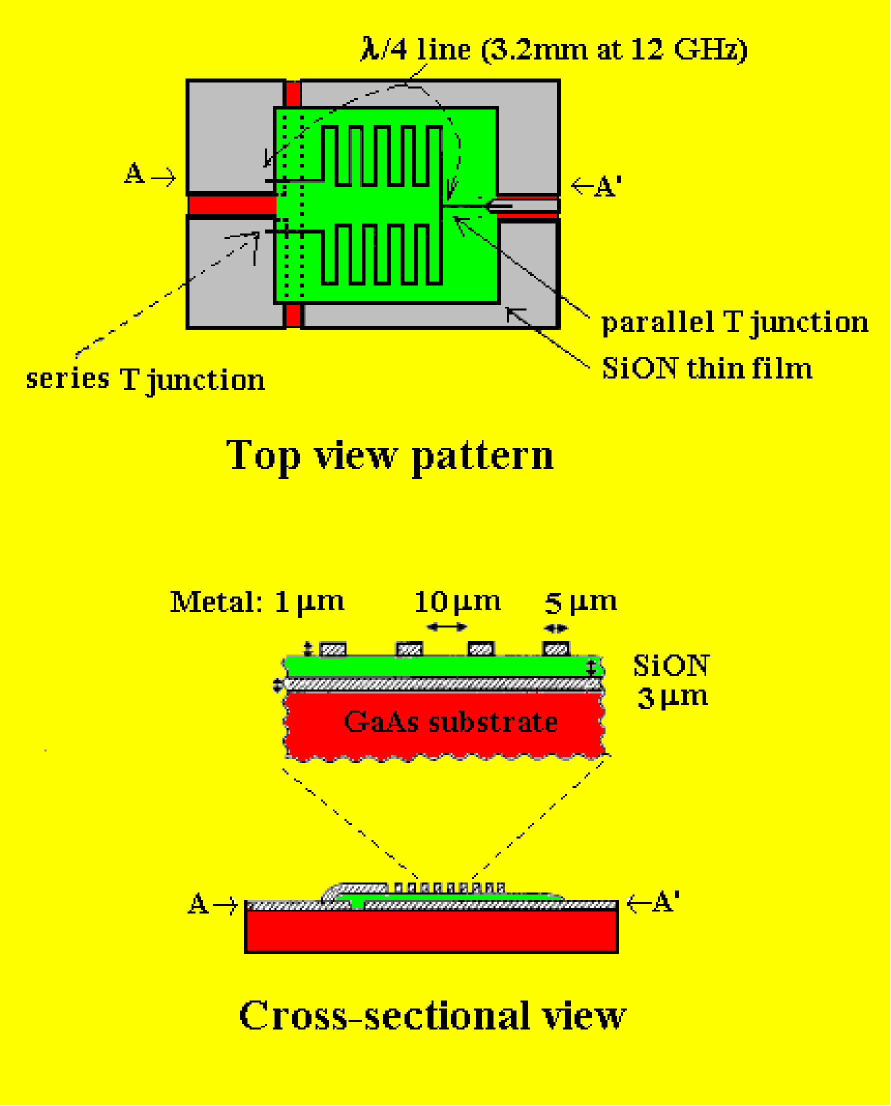


Fig. 1.11. A compact MMIC magic T structure using TFMS TL [16].

The first reason for such a successful miniaturized design lies in the fact that the TFMS 50-Ω TLs can be fabricated on a thin 3-μm silicon oxynitride (SiON) substrate of width 5 μm and pitch 15 μm for the adjacent TFMSs. The second reason, which is less noticed, is the use of meandered TFMS structure. These two reasons make the quarter-wavelength TFMS quite compact in area.

However, the meandered TFMS has two drawbacks. First of all, the linewidth W of the TFMS will become the single controlling parameter for varying the characteristic impedance Z_c, once the process parameters, such as the substrate thickness (h) and the dielectric material, are decided. This makes a strict limitation over the use of a high-impedance line since the MS will become unrealistically narrow. Furthermore, many microwave hybrids and passive circuits, such as couplers, filters, and power dividers, mandate the TLs of wide-range characteristic impedance [25]-[27]. Consequently, the design of the TFMS passive and hybrid circuits will become a challenging issue.

Secondly, the meandering of the MS dramatically alters the propagation characteristics of the bound EH_0 mode in phase constant β and characteristic impedance Z_c. Such drastic changes in β and Z_c are due to the result of coupling among the nearby TFMSs and the right-corner bends of the meandered lines. Thus, a larger ratio of the adjacent line spacing (l_g) to the substrate height (h), typically greater than two [15], is applied to avoid serious degradation in guiding characteristics. This, however, adversely affects the efforts for making miniaturized microwave circuits.

Therefore, one main theme of this dissertation is to develop a new synthetic quasi-TEM TL with more degree of freedom for varying the propagation characteristics. This technique should possess the properties of wider choice of characteristic impedance and flatter less sensitive propagation characteristics in a very compact area. And it should be completely compatible with the mature manufacturing processes, and be of no need to change the process parameters.

1.2 Background and motivation of miniaturized beam-steering antenna

Apart from a great desire for making miniaturized RFIC or microwave circuit using synthetic quasi-TEM line; the is, on the other hand, a great need for making synthesized higher-order mode microstrip line at higher order. A number of commercial opportunities are emerging in the wireless communications, imaging and automotive electronics markets for active, and "smart” antenna systems. The beam steering/scanning is an important and necessary function for the smart antenna systems. For example, indoors commercial wireless phones, indoors wireless local area networks, cellular wireless phones, and base-station antennas usually require tilted main-beam. On the other hand, microwave antennas for burglarproof system, automotive collision avoidance system, searching radar, tracking radar, and auto tolling system, usually require scanning function of the main-beam [28]-[30].

In the following, we will illustrate the typical beam-steering methods and their limitations. The beam-steering methods are divided into two kinds roughly, that are mechanically scanning methods and electronically scanning methods. Mechanically scanning methods mostly utilize mechanical holding arm and rotating control platform to steer the beam. These methods have limited scanning speed. On the contrary, the conventional electronically scanning methods mostly utilize phase-array antenna structure to steer the beam. The rapid scanning control can be easily implemented. The configuration of phase-array antenna structure is shown in Fig. 1.12.

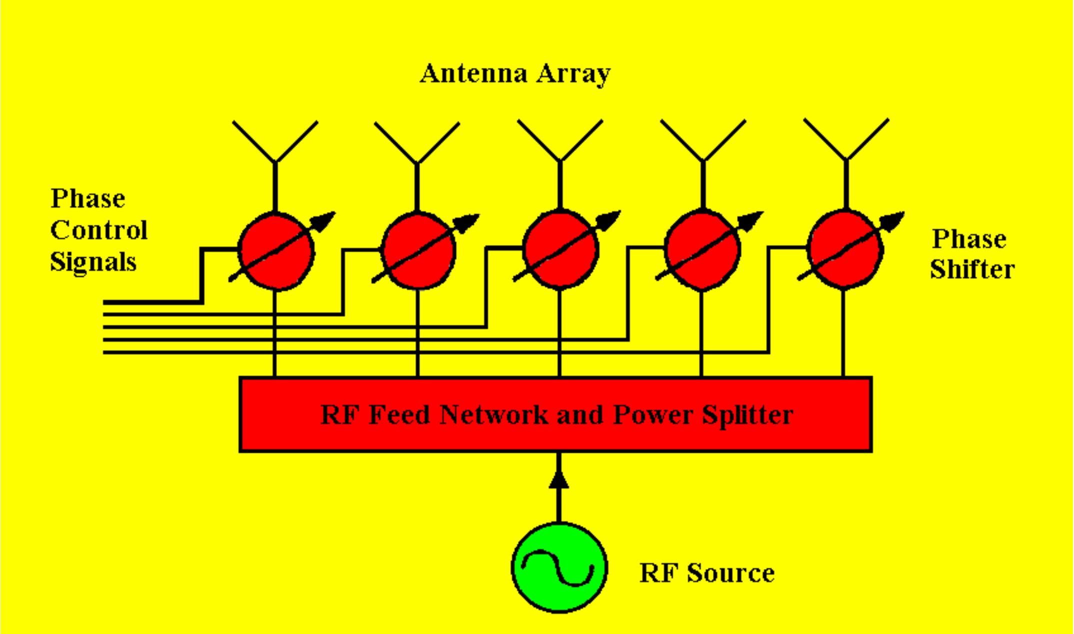


Fig. 1.12. Configuration of phase-array antenna structure

Half wavelength patch antennas in half wavelength spacing construct typical antenna array. The lengths of the feeding, the matching networks and the multi-port power splitter are approximately close to the order of the wavelength at the microwave operational frequency. Except for the large areas of the antenna array, the feeding network and the power splitter are required, and many expensive phase shifters are also needed. This makes miniaturized, low cost and simple making phase-array antenna structure rather hard to achieve.

Many studies have been presented for the purpose of miniaturization, low cost, and/or simple making for the beam-steering antenna structure [30]-[50]. The representative methods will be summarized as follows.

(a) By the use of the guided leaky-mode propagation characteristics of leaky-wave antennas, a controllable direction of fan beam can be achieved. This can replace a larger area in one-dimensional (1-D) linear array, and hence get a miniaturized beam-steering antenna [41]-[44].

(b) By the application of the coupled oscillator method, the injection locking method, phase locking or phase tuning methods, beam steering without using phase-shifter can be feasible [30], [45], [46]. This can eliminate the need of the expensive phase-shifter circuitry, and hence get a low-cost beam-steering antenna.

(c) By the utilization of the loaded reactance component methods, the main beam can be controlled since the current distribution is changed as the inductors are put into the wire antenna [48]. This method possesses all three properties of compactness, low-cost, and simple making.

Based on the above technologies, a new interdisciplinary design method is presented in this dissertation. This method utilizes the guided leaky-mode propagation characteristics of microstrip at first higher order, and integrates both the phase-shifterless scanning method and the loaded reactance component method in the implementation [51]. An excellent result of a miniaturized, low cost and simple making beam-steering antenna can then be possible.

Hence, the second objective of this dissertation is to develop a novel synthetic TL structure such that one can vary the phase constant of the EH_1 leaky mode of the TL by incorporating a periodic, capacitor/varactor-loaded leaky line. This structure can realize a novel synthetic beam-steering leaky-wave antenna in fewer controlling elements. And it will be low-cost and occupies smaller area than the phase array. The phase array utilizes many expensive phase-shifters in larger area.