Chapter 1

Introduction

Planar transmission lines with a single ground plane (microstrip line) for microwave signal propagation drew the attention of many researchers when Assadourian and Rimai [Assadourian et al. 1952] published the simplified theory on microstrip transmission systems. Their solution was very much approximate, and more rigorous studies [Black et al. 1955; Wu 1957] followed with more exact results. When Hyltin [Hyltin 1965] analyzed the microstrip line on semiconductor dielectrics, it opened the opportunity of not only using a high quality interconnection line between different microwave functions, but also fabricating multiple transmission line devices on a common semiconductor substrate. This offered improved performance and system-level reliability advantages, because it eliminated the need for packaging of each individual element and reduced the problems associated with parasitic inductances and capacitances in the microwave circuits. Subsequent theoretical studies showed that when these microstrip lines are fabricated on multi-layered semiconductor substrates (e.g., SiO_2 on Si), they support three distinct modes of propagation [Guckel et al. 1967; Ho et al. 1967], namely the skin-effect mode, the quasi-dielectric mode, and the slow wave mode. Hasegawa [Hasegawa et al. 1971] experimentally verified these modes of propagation on SiO_2 - Si microstrip line. It has also been shown that the transition between these modes is a function of frequency and the widths and conductivities of the semiconductor substrate layers.

The initial motivation behind this research work was based on these basic observations: by changing the effective widths of the multi-layered semi-conductor substrates, which can be done electronically or optically, it was believed changes in the propagation constant of the transmission line resulted. Concentration was focused on co-planar waveguide (CPW) type transmission line to make either a resonator [Islam 1990] or phase shifter [Islam et al. 1991], for its planar structure and the ease of using optical power as the controlling signal. In addition, optical power was chosen as the controlling mechanism over the conventional electronic control because of its greater potential bandwidth and the complete isolation between the modulating and carrier signals.

A variety of research has been performed in the area of planar transmission line devices made on semiconductor substrates, which are controlled through voltage or light (e.g., [Lee et al. 1980; Herczfeld et al. 1985; Neidert et al. 1985; Hietala et al. 1987; McKaughan et al. 1988; Kaiser et al. 1989; Cheung et al. 1990]). Phase shifters were implemented electronically using Schottky-contacted microstrip or CPW conductors. Use of optical power to make a phase shifter was first demonstrated by Chi H. Lee [Lee et al. 1980] on a high resistivity semiconductor dielectric waveguide structure. Following C. H. Lee's work, optical control of devices include metal-semiconductor field-effect transistors (MESFET) [Salles 1983], high electron mobility transistors (HEMT) [Simons 1987], oscillators using impact avalanche transit time (IMPATT) diodes [Seeds et al. 1967] and MESFETs [Salles et al. 1981], p-i-n diodes [Herczfeld et al. 1985] and phase shifters [Cheung et al. 1990]. An optically-controlled phase shifter was presented [Cheung 1985] with low phase shift but moderate optical power. The performance was improved by combining both Schottky and optical control [Cheung et al. 1990]. A further improvement was achieved using advanced processing techniques, where thin epitaxial semiconductor (GaAs) layer was peeled off and transferred onto a high resistivity substrate [Islam et al. 1991].

Besides the experimental work, a strong motivation existed to formulate an accurate equivalent circuit model to explain the propagation characteristics of a Schottky-controlled or an optically controlled CPW phase shifter. Analysis of a Schottky-contacted device includes modeling of both the series and shunt part of the circuit. Previously CPW structures were analyzed both with quasi-static approximation and fullwave calculations [Davis et al. 1973; Tzuang et al. 1986]. All the quasi-static analyses avoided accurate conductor loss calculation, and therefore were approximate and failed to match with experimental results (as discussed in Chap. 4). On the other hand, fullwave calculations using numerical techniques require extremely large amounts of computer time and memory, and therefore, are difficult to use for design. In this dissertation, along with measurements on the CPW phase shifter, an accurate circuit model is presented, which takes conductor loss into consideration as well as loss due to the semiconductor substrate. As a result, this quasi-static characterization provides a complete picture of the propagation mechanism of a Schottky-contacted phase shifter.

Chapter 2 of this dissertation discusses the processing techniques involved in the fabrication of the CPW phase shifter. The phase shifter is in the form of a long transmission line with two large ground planes and a thin center conductor and two thin gap regions between the ground planes and the center conductor. It was extremely difficult to make such a device 1 cm long with 7 µm of minimum feature size with the Departmental fabrication facilities. Different approaches were tried to get better yield on processed devices, with a polyimide lift off process being very successful in terms of high yield. Besides the regular processing techniques, an advanced epitaxial lift off technique (ELO) is also discussed [Tsao 1993], where the thin (1 µm - 3 µm) epitaxial GaAs layer is peeled off from its parent semi-insulating substrate and transferred onto an alternative substrate to get better performance.

Chapter 3 discusses the conductor loss calculation of a CPW structure with more than one micron thick conductors. The model, based on the quasi-static conformal mapping technique, calculates the complete series impedance of the CPW structure. This technique is simple to use and extremely efficient from a computational perspective, especially when compared to other conductor loss calculation techniques. In this approach, the non-uniform current distribution along the conductors, due to both skin-effect and proximity effect, are transformed into a uniform shape at the price of non-uniform resistance of the conductors in the mapped domain. The mapped conductor surfaces are then analyzed and a scaled surface impedance is calculated, from which the series impedance is evaluated. This method shows an accurate match with experimental results. The model results are also compared with other existing quasi-static calculations where a clear superiority of our model is established.

Chapter 4 discusses the model for the lossy shunt circuit of the CPW phase shifter. This analysis gives the physical interpretation of the actual propagation control mechanism of a Schottky-contacted CPW phase shifter. This chapter introduces the series resistance effect in the epitaxial layer which helps to explain the change of propagation constant of such a phase shifter.

Chapter 5 discusses the experimental results of a Schottky-contaced CPW phase shifter. The phase shifter performance is measured both for Schottky-control and for optical control. The best result is obtained when the phase shifter is optically-controlled with the ground planes kept at a fixed reverse bias. In addition, the epitaxial layer of GaAs was peeled off and transferred onto a quartz substrate [Islam et al. 1991] to obtain improved performance. In addition to these experimental results, different comparisons with other phase shifters, including some commercially available ones, are made to evaluate the performance of our phase shifter. It has been observed that for a frequency range of dc - 40 GHz, this phase shifter is superior or unique compared to any other available phase shifter.

Chapter 6 identifies the main contributions of this dissertation and summarizes the complete work. In addition, a brief discussion of future direction of this work is presented in this chapter.