Chapter 1

Introduction

The emerging technology of infrared and millimeter wave detection has required the development of small low cost integrated circuit antennas. Since the millimeter and far infrared (FIR) spectra are between optical and microwave frequencies, the technologies used to realize practical, efficient structures have elements of both optical and microwave technologies. The usual millimeter wave imaging system has both lenses and antennas [1-8]. At millimeter and FIR frequencies phased arrays are difficult to build. Imaging arrays, however, are useful at these frequencies because they provide a means of gathering information over an area without any mechanical scanning[1,6]. There are several constraints on an imaging array antenna element. The first is that it should be small enough to allow the elements to be placed sufficiently close together to provide good resolution of the image. Another important consideration is that it have a beam pattern that couples well to the optical system that focuses the electromagnetic energy on the array. Printed antennas built on quartz or semiconductor substrates are a good candidate for this type of system, but the foregoing constraints mean that the antenna will probably couple well to substrate guided modes if the substrate is electrically thick.

There has been a considerable amount of work done on microwave printed circuit antennas for frequencies between 500MHz and 60GHz [9]. At these frequencies, it is possible to use electrically thin substrates (usually grounded substrates), and therefore losses to the guided waves are small. Also, the properties of the antenna depend mainly on the design of the printed metal pattern. When the substrates must be thick compared to a wavelength, the properties of the antenna are now strongly governed by the properties of the dielectric as well as the metal pattern of the antenna. Since the fabrication of printed millimeter wave antennas often involves building printed antennas on a slab of dielectric that is a substantial fraction of a wavelength thick, the antenna will require design of both the receiving metallic structure and the dielectric substrate upon which it is built. As discussed in [1] and [2], the amount of power that the antenna couples to the guided modes in the substrates becomes comparable to, or greater than the power radiated to air as the substrate thickness is increased. This dissertation focuses on the design of a millimeter wave antenna that could be built on an electrically thick dielectric substrate, such as quartz, and have a reasonably good coupling efficiency to air. Both the antenna and the substrate are designed to enhance the radiation-to-air properties of the antenna and reduce the coupling to the guided waves in the substrate.

Pioneering work in this field is outlined by Rutledge and Neikirk [1] which describes some of the basic problems associated with design and construction of antennas, waveguides, and detectors for use in the millimeter wave and FIR spectra. Currently, there are two commonly used approaches which allow the antenna to couple efficiently to air. The first is to make the supporting substrate electrically thin, which usually means that the substrate is less than about one hundredth of a dielectric wavelength thick [2]. For such thin substrates, printed antennas couple only weakly to guided waves (also called surface waves) in the dielectric substrate. At 94GHz, however, on $\varepsilon_r = 4$ (where ε_r is relative permittivity) material (quartz) an electrically thin substrate is only about 16μm thick, while for a substrate with $\varepsilon_r = 13$ (GaAs) the thickness is only 9μm. Fabrication of printed antennas is quite difficult on such thin substrates, although Rebeiz et al [7] have reported results for dipoles on silicon oxynitride membranes which were electrically thin at frequencies up to 700GHz.

A second approach to achieve efficient coupling makes use of an infinitely thick, rather than infinitesimally thin, substrate. In this case a dielectric half space is approximated through the use of a substrate lens [1,4,5,6,8]. Here, since the two surfaces of the substrate are no longer coplanar, there are no guided wave losses. In addition, with this configuration, a printed antenna has a natural tendency to couple much more strongly into the dielectric. However, the use of a substrate lens presents difficulties in millimeter wave imaging applications because the lens must be large compared to the array size so that off axis aberrations are small, and at millimeter wave frequencies this can be quite large. It has also been noted that there are difficulties with pattern and coupling efficiency due to taper losses for antennas on substrate lenses [4,7]. In addition to the poor beam patterns, at certain frequencies the absorption losses in the dielectric lens material are not small, and a wave propagating through the lens undergoes substantial attenuation.

This work uses layered grounded substrates to produce usable beam patterns, efficiencies, and impedances for printed antennas built on electrically thick dielectric substrates. This approach has the advantage of being simpler to fabricate than membrane-supported antennas. It also has the potential to produce better beam patterns than the substrate lens-coupled antennas.

The general properties of waves in stratified media have been of interest in acoustics as well as electromagnetics [10]. Propagation of waves, both acoustic and electromagnetic, through the earth can, in some circumstances, be modeled as waves propagating through a stratified, layered, medium. The properties of a dipole radiator over a layered medium have been of interest to radio engineers for a number of years [11,12]. In some cases the earth can be modelled as a half space of dielectric which is similar to the problem of a printed antenna on a lens-coupled substrate [13]. More recently, the problem has been of interest in the mircowave community with regard to printed circuit antennas [14-23]. In [14] the properties of a microstrip dipole radiating into a lossy, layered dielectric medium are presented for modeling electromagnetic power deposition in biological tissue for hyperthermia treatment of cancer. In [15,16] the radiation properties of a dipole on a grounded two layer substrate radiating into air are discussed. In [15] the effect of a cover layer on the radiation-to-air pattern and on the guided modes in the substrate are discussed. In [16-18] the focus is on using cover layers to enhance the gain of the antenna. In [20] and [21] the effect of a cover layer on resonant length and on the input impedance of the printed dipole are discussed in. In [22] the effect of a thin cover layer of dielectric on the resonance frequency of a microstrip patch antenna is considered, but the dielectric layer is treated as being unintentionally introduced and not utilized to advantage. In [17] the radiation-to-air properties of a dipole element on a grounded layered substrate are presented with the emphasis on high gain structures, but the effects of the guided waves and losses in the ground plane are not discussed. Also, a low loss material with $\mu_r = 4$ (where μ_r is relative permeability) and $\varepsilon_r = 1$ is used, although this author is not aware of any materials with these properties at millimeter wave and FIR frequencies. In [18] and [23] the requirements for creating omnidirectional beam patterns and azimuthally symmetric beam patterns are discussed. For our purposes, however, a beam pattern which matches well to the optical system that the array is intended to operate with is desirable. Also, it is desirable to couple as little power to the guided waves as possible, since this will increase cross-talk between elements and decrease the efficiency of the antenna.

The basic spectral domain method for analyzing printed transmission line structures on layered dielectrics is presented by Itoh in [24] although a similar approach had been used earlier to characterize microstrip transmission lines [25]. It has also been used in some of the first rigorous full-wave analysis of microstrip patch antennas [26-27]. This approach had the advantage over previous methods applied to this problem that it did not rely, for its validity, on the substrate to be electrically thin. This method has also been used to characterize resonance frequencies and beam patterns of a coupled twin slot reciever that uses the twin slots both as the resonator element for a local oscillator as well as the receiving antenna [28]. The spectral domain method is used in this dissertation to analyze the impedance of slot antennas on open layered dielectric structures. We use the twin slots in the even mode and couple the antenna structure to a detector through a microstrip line.

Our approach is to constrain the material choices to those materials which are known to be low-loss (i.e. a loss tangent of 0.001 or less) at millimeter wave and FIR frequencies. We include the effect of ground plane losses and dielectric losses for the radiation-to-air calculations. We discuss the radiation properties of both slots and dipoles. However, we only present calculations and measurements of impedances for slot antennas because we believe that these are the most practical antennas for use in a two-dimensional imaging array. This is because the slot antenna ground plane can be used to isolate the feed network and reciever electronics from the incident radiation.

The organization of this dissertation is as follows. Chapter 2 describes the analytical techniques that will be used to calculate beam patterns, efficiencies, and input impedances of the antenna and substrate configurations that are considered. Chapter 3 describes how broadside-spaced twin element antennas can be used on an electrically thick, single layer, grounded dielectric substrate to increase the radiation-to-air efficiency of the structure. Most of the material presented in this chapter appears in [29]. Chapter 4 describes how layering the substrates can produce desirable beam patterns and further increase the efficiency of the printed antennas. Calculations of efficiency and beam patterns are presented and some measured beam patterns are also presented. The material in this chapter can be found in [30,31]. All of the calculations performed in chapters 3 and 4 used infinitesimal current sources. Chapter 5 describes the results of impedance calculations and measurements performed to characterized microstrip-fed slot antennas. In these calculations slots of finite width and length were used. It was found that the microstrip-fed slot antenna-feed structure has an input impedance that allows it to be used with common detectors such as bolometers or Schottky diodes. Some of the material presented in this chapter is described in [32].