1 Introduction

The last decades have witnessed a rapid evolution of wireless sensing and communication systems aimed at the consumer market. The antenna is a key component in any of these systems and the selection criteria for a commercial success include among other things the antenna performance, size, weight, and cost.
Conventional antennas most often are parabolic reflectors. Although they are efficient radiators and considered to be of high gain, they have large masses and due to their curved shapes they are bulky and occupy large spaces. On the other hand, planar printed reflectarray antennas have gained a wide popularity due to the ever-growing trend toward system integration and miniaturization. They are advantageous in terms of low profile, lightweight, ease of fabrication, and low cost. In this thesis printed metallic patches on dielectric substrates either with or without backside metallization are investigated and utilized for the design of planar reflectarrays for a wide variety of antenna applications. The printed reflectarray surfaces can be manufactured using simple and low cost etching processes, especially when produced in large quantities. Figure 1.1 shows one example of the investigated configurations in this thesis.

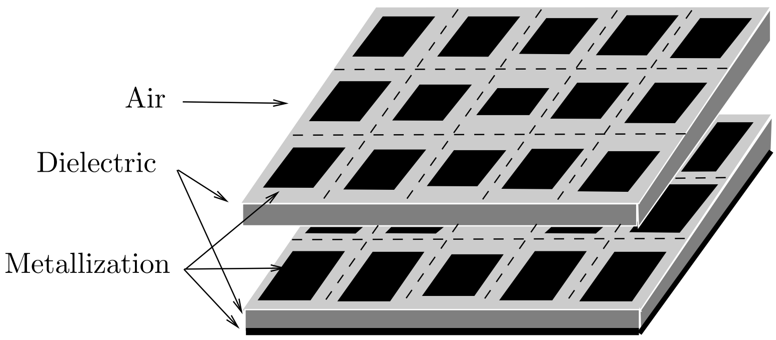

Figure 1.1: Example of a multilayer grounded configuration which has been investigated in this thesis.

This thesis is structured as follows:
Chapter 2 deals with the theoretical part of this work. The developed program permits the determination of the scattering parameters and the Green's function of printed arrays of patch elements under the local periodicity approximation. Although the printed patch elements may have any arbitrary shape, they are restricted to simple rectangular ones in this thesis. The calculations are based on the Spectral Domain Immittance Approach (**SDIA**) in which the configuration is transformed to its equivalent transmission line model and the Green function can easily be calculated analytically. According to the patch size and/or the substrate thickness, the configurations are analyzed to the maximum range of the reflection phase, the sensitivity to fabrication tolerances, and the element bandwidth. In order to obtain increased bandwidth performance, the program is extended to handle twolayer configurations with any patch size on the first layer and the second layer as well. Furthermore, the program is extended to handle for any angle of incidence the direct reflection (angle of incidence = angle of reflection) and higher orders of reflection (angle of incidence ≠ angle of higher orders of reflection) and any linear polarization. Finally, to prove the accuracy of the developed program, the characteristics of the analyzed configurations are compared to results of some other developed programs [1, 2].
Based on the calculations in chapter 2, different antenna concepts are presented in chapter 3. The principle of a planar printed reflectarray antenna is first explained by means of the conventional parabolic reflector antenna; since the reflection phase angle is related to the patch size, each individual patch element can be considered as a fixed phase shifter. In the second step, the concept of a folded reflector antenna with a twist reflector – rather than a normal reflector without polarization twisting – is discussed. The focussing of the antenna is modified by twisting the electromagnetic fields together with a polarizing grid or slot array, leading to a reduced antenna height. The goal is the design of antennas with very low profiles. To this end, optimizations regarding antenna height reduction are made for the folded reflector antennas. Additionally, a double and a triple folded reflector antenna with very low profiles were developed. To improve the antenna performance (gain, bandwidth, sidelobe level, etc.), twolayer reflector antennas are designed, investigated, and their performances are compared to those of single layer ones. Other antenna concepts include: a 27.6 GHz folded reflector antenna with an integrated quasi-optical filter for an excellent sidelobe reduction by up to 15 dB, a low profile dual-frequency antenna for point-to-point and point-to-multi point communication at 60 GHz/900 MHz (the two antennas are integrated in a common aperture), and a multibeam antenna for

76.5 GHz with three feeds producing three beams and a total scanning range of 12° for mm-wave automotive radar systems.
In chapter 4, new artificially made structures so called Photonic Band Gap structures (**PBG**), are investigated and combined with simple antenna elements for gain enhancement. These structures have periodic features and forbid the propagation of electromagnetic waves within certain range of frequencies. However, the properties of the structures change when using them as superstrate (cover) layers to antenna elements; a defect mode inside the structure appears and opens a localized mode inside the frequency gap (forbidden band) of the structure. At this frequency the directivity of an antenna element in combination with such a structure is greatly enhanced. An antenna of this kind with a low profile is proposed and verified in the Ka-band frequency range.

2 Theoretical backgrounds

The theoretical part of this work determines the characteristics of electromagnetic fields (reflection, scattering, diffraction, etc.) of plane waves on plane configurations consisting of single layer or multilayer printed arrays of metallic patch elements on dielectric substrates.
Different approaches can be applied to solve the problem of scattering. When the dimensions of the radiating object are very large compared to the wavelength, geometrical optic rules(**GO**; direct, reflected and refracted rays) [3] can be applied. Optical as well as microwave problems can be solved by this method, for example, determining the contours of a parabolic reflector antenna. If the property of the object is taken into account then the theory of diffraction can be applied [4, 5].
On the other hand, if the dimensions of the radiating object are near a wavelength, then a simple **GO** method cannot be applied anymore. A full wave approach has to be applied for solving the problem. In this case, the equations have to be solved under all boundary conditions. The problem can either be solved in the time or the frequency domain.

One of these approaches is the Finite Difference Time Domain method (**FDTD**) [6–8]. The method is formulated by discretizing Maxwell's differential equations over a finite volume with respect to the original Cartesian coordinates in time and space. The derivatives are then transformed into difference approximations. Although **FDTD** can model complex structures inside an enclosure with suitable boundary conditions, it often requires considerable amount of computing time and memory; certain precalculations have to be taken into account when the method is applied on an open-region problem in which the region is truncated to a finite size.

Another approach is called the Mode Matching method (**MM**) [9,10], which is a powerful method for analyzing waveguides with variable cross-sections. In [11], the **MM** method is applied to infinitely extended periodic arrays of printed structures. The analysis can be simplified by considering one single unit cell parallel-plate waveguide and applying the appropriate periodic boundary conditions. The analyzed structures, however, have to be shielded with electric and magnetic walls. A further restriction to the method is that it can handle only the case of a normal incident wave to the periodic structures.

The Spectral Domain Approach (**SDA**) [10] is an efficient method for solving the scattering problem of configurations composed of printed metallic structures and dielectric layers. The method is formulated by describing the electric field through an integral equation [12] of induced current distribution on the printed metallic structures and the Green function (the Green function explains the relation between the current and the electric field). This integral equation is then solved in the spectral domain after applying a Fourier transformation for one, two, or three axes of thin conductors. Through this transformation the Green's function is especially simplified because the convolution integral in the space domain is transformed to a simple multiplication in the spectral domain.

By applying the Method of Moment (**MoM**), which is a popular technique for discretizing a continuous operator equation, the integral equation is then converted into a matrix form. This procedure leads to an analytical solution of the problem.

Plane configurations, either open or closed on the top of the layers, are very suitable to be solved the **SDA**. The method permits the calculation of the scattering parameter for incident plane waves, which are either normal incident or oblique incident to the structures.

2.1 Spectral Domain Approach for multilayer configurations

The Spectral Domain approach (**SDA**) is especially suited for solving the scattering of a plane wave from single and multilayer structures. Figure 2.1 shows an example of a twolayer configuration that will be investigated in this work, however, some restrictions have been applied to the configuration in order to simplify the method of solution:

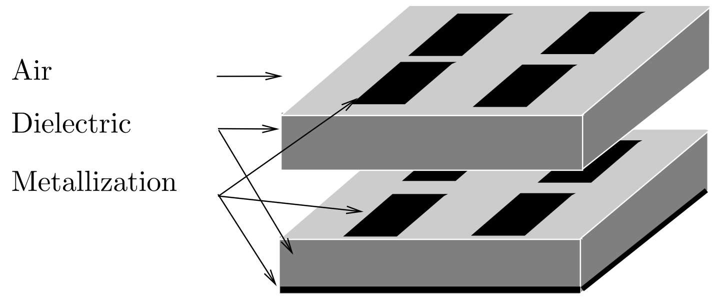

Figure 2.1: Exploded view of a multilayer grounded configuration consisting of two arrays of periodic patch elements printed on the top of each dielectric substrate.

- Perfect conductors. As a result, ohmic losses on conducting areas are negligible.
- The conducting layers are infinitely thin. As a result only tangential currents on a conducting area have to be considered.
- The dielectric layers of a configuration are infinitely expanded, homogeneous, and isotropic.
- The array of microstrip-patch elements is periodic and infinitely expanded.

In this work the scattering problem will be expressed as an excitation problem; the patch elements have to be illuminated by an electromagnetic field that is a plane wave. **MoM** will then be applied to transform the scattering problem into a linear set of equations; the current density function is then expressed through a set of known basis current functions with unknown coefficients. Once the coefficients are known, the scattering parameters can easily be found. Since the arrays of patches are periodic and illuminated by a plane wave, the Floquet's theorem [13] can be applied: on the one hand, the current density functions for the whole structures can be represented through a unit cell (elementary cell), with the consequence that the current density function has to be evaluated for only the unit cell and hence, the system of equations is minimized; on the other hand, the reaction integrals (the scalar product of the basis and test functions, together with the Green's function used in this work, lead to two-dimensional integrals) are reduced to a two-dimensional summation, and the numerical effort is further reduced.

However, if the arrays of patches are quasi-periodic, then the Floquet theorem cannot be applied anymore and the current density functions have to be evaluated for each element of the array, leading to enormous computation efforts. In [14] a mixed integration method for an efficient approach for solving the reaction integrals in spectral domain is presented; the integrand is partly evaluated in Cartesian coordinates wherever possible and the other part of the integrand which is highly oscillating is evaluated in polar coordinates by Filon's method [15]. This leads to a drastic reduction in the calculations. The remaining part of the integral, the part in the vicinity to the poles, is evaluated in a conventional way using the residual theorem.

2.1.1 Integral equations in space and spectral domain

To specify the electric and magnetic fields of a scattering problem, the relationship between electric and magnetic fields, respectively, and the current density functions can be expressed through integral equations [10]

$$\vec{E}(x,y,z) = \iiint\limits_{V'} \Big\{ \vec{\vec{G}}_{E,J}(x,y,z,x',y',z')\, \vec{J}(x,y,z,x',y',z') \\ + \vec{\vec{G}}_{E,M}(x,y,z,x',y',z')\, \vec{M}(x,y,z,x',y',z') \Big\}\, \mathrm{d}V' \,,$$

$$\vec{H}(x,y,z) = \iiint\limits_{V'} \Big\{ \vec{\vec{G}}_{H,J}(x,y,z,x',y',z')\, \vec{J}(x,y,z,x',y',z') \\ + \vec{\vec{G}}_{H,M}(x,y,z,x',y',z')\, \vec{M}(x,y,z,x',y',z') \Big\}\, \mathrm{d}V' \,. \quad (2.1)$$

$\vec{E}$ and $\vec{H}$ are the electric and magnetic fields, $\vec{J}$ and $\vec{M}$ are the electric and magnetic current densities, respectively, and $\vec{\vec{G}}_{E,J}$, $\vec{\vec{G}}_{E,M}$, $\vec{\vec{G}}_{H,J}$, and $\vec{\vec{G}}_{H,J}$ are the Green's functions. Since the metallized areas have been assumed to be of zero thickness in this work, only tangential currents have to be considered. As a result, the three-dimensional volume integral will be reduced to a two-dimensional integral over the area of the metallized structures along the x-axis and the y-axis. Further on, magnetic currents on the metallized structures do not exist. From these two considerations it follows that the two equations in (2.1) can be simply reduced to

$$\vec{E}(x,y) = \iint\limits_{A'} \Big\{ \vec{\vec{Z}}_{E,J}(x,y,x',y')\, \vec{J}(x,y,x',y') \Big\}\, \mathrm{d}A' \,,$$