Technische Universität
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Diploma Thesis

Implementation of a 8x8-Butler Matrix in Microstrip

Accomplished at Institut für Nachrichtentechnik
und Hochfrequenztechnik at Technische Universität Wien
by

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Abstract

The so called 8x8 Butler matrix is a passive circuit, which gives the ability to get a main beam from an antenna array into one of eight possible directions

This diploma thesis has showed that it is possible to implement an 8x8 Butler matrix in microstrip completely in a 2-dimensional structure. Even tough, the Butler matrix perform a satisfactory antenna pattern with the ability to achieve sidelobes lower than -17 dB within the ISM-band at 2.45 GHz by superposition of two adjacent beams. The gain of the main beams are about 12 dBi, which gives that the circuit not suffers from extensive losses.

A crossover with high isolation between two signals is achieved by a structure made up of two connected broadband 90 degrees hybrids. Otherwise, phaseshifters and 90 degrees in the Butler matrix circuit are implemented without broadband structures.

The antenna pattern form an antenna array is predicted during the implementation by simulations of the signal flow in the structure.

Preface

Today's mobile communication is calling for higher data rates and improved transmission quality between the mobile and the base station. To fulfil future capacity requirements, new systems are developed that try to take advantage of the spatial separation of the users. This can be made by means of adaptive antennas at the base station. Essentially, there are two different methods for adaptive antennas, either Base Band-processing or RF-beamforming. The first one relies on powerful adaptation algorithms to form the best beamshape for the actual situation, so called digital beamforming. The performance of such an accurate, but rather expensive concept of digital beamforming, has to be compared to the performance of a system for a low-cost applications. Such a low-cost system could use a passive beamforming network utilising a Butler matrix. To investigate the advantages of these antenna concepts, two prototypes capable of handling data rates in excess of 1 Mbit/s are they currently being implemented at the workgroup of mobile communication at the INTHF[1]

As an ERASMUS-student, I had the opportunity to join the team and to design some parts in the passive beamforming system, termed SwItched beam TEstbed (SITE), namely the Butler matrix and the patch antenna.

The first chapter of this report introduces the concept of Butler matrices and the purpose and requirements for this Diploma thesis. Chapter 2 develops the concept of phased arrays and gives a brief discussion about the theory behind Butler matrices and Microstrip lines. The simulation setup and the software used are described in chapter 3, while Chapter 4 shows the manufacturing process and details the implementation of the different components of the Butler Matrix. Chapter 5 discuss the simulation results and explains the implementation and measured results of the 4x4 Butler Matrix and the 8x8 Butler Matrix. Chapter 6 gives a brief explanation of the implementation of the antenna, while the measurements of the pattern of the whole system in an anechoic chamber are covered by chapter 7. In Chapter 8 the report ends up with a conclusion and with comments to the whole work. The last pages are appendices with the complete results shown and listings of the MATLAB-code for the simulations of the Butler Matrix.

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Chapter 1

Introduction

This section gives you some information about reasons for a Butler matrix in today's or the next generations mobile radio communication. You will also find a discussion about the requirements for the antenna pattern leading to the general requirements for the Butler matrix and the antenna.

1.1 System Overview and Problem Specification

The work done in this thesis is part of a testbed developed at the Technische Universität in Vienna which should investigate the possibility to achieve capacity enhancement in mobile radio communication by using an RF-beamforming network. The actual testbed, termed Switched Beam Testbed (SITE), is designed for the ISM-band at 2.45 GHz and should be capable of handling data-rates in excess of 1 Mbit/s.

A simplified block structure of the SITE-system is shown in Figure 1.1. The base station system comprises an antenna, a Butler matrix, a beam selector and a base station. The antenna array creates a pattern, which has its main beam in the direction of the user. The tool to create this appropriate pattern is a Butler matrix, which feeds the elements of the antenna with signals of appropriate phase and amplitude. The Butler matrix is completely implemented in hardware and give the ability to choose between one of eight discrete beam directions, a so called passive beamforming network.

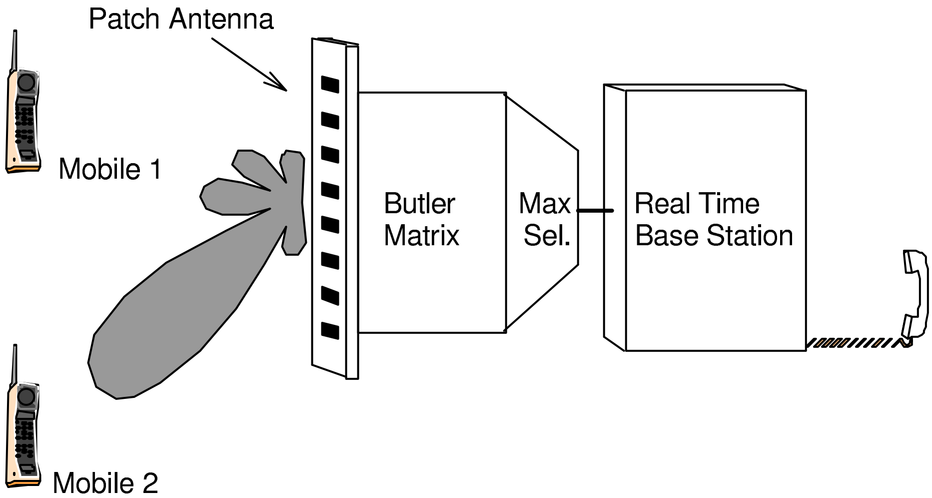

Figure 1.1: Overview of the SITE-testbed

A detector is placed at each output of the Butler matrix, which in combination with a hardware maximum-selector allows fast selection of the strongest signal. This signal is transmitted to a Real Time Base Station System. On the whole, the SITE-testbed is a low-cost adaptive antenna system capable of performing real-time transmission at high data-rates. When the tests are performed, one transmitter acts as the appropriate mobile station, whereas another transmitter in another direction acts as interferer. Now it is up to the system to achieve the best result for the communication between the appropriate mobile and the base station. This requires an antenna pattern with low sidelobes and narrow beams, and of course, an excellent performance of the logic behind the Butler matrix.

This gives us the major goal for my diploma thesis: (a) *To implement a Butler matrix which allows us to achieve a satisfactory antenna pattern,* and (b) to manufacture the antenna array, which is based on earlier work performed at INTHF.

1.2 Pattern Requirements

The main goal for the antenna and the Butler matrix is of course to achieve an antenna pattern as good as possible. Before we can go on, we have to define the meaning of a good in our context. Therefore, I will describe the antenna pattern created by an antenna fed by a Butler matrix look like and state which features that are the most undesired.

While phased arrays have a single input port, multiple-beam systems have a multiplicity of input ports, each corresponding to a beam with its peak at a different angle in space. A typical antenna pattern from an 8x8 Butler matrix connected to a eight element antenna array is shown in Figure 1.2. In this Figure all of the eight possible single beams are illustrated simultaneously. The pattern of a single beam of the antenna array consists of a main beam, and beams in other directions, termed *sidelobes.* These sidelobes are unwanted for several reasons. They give radiation in a direction where there is no user, which could cause interference with other users. Conversely, radiation in an unwanted direction allows also reception of an interferer transmitting from this direction Furthermore, radiation is also power, which gives that a lower part of the intended power reaches the user and losses are introduced.

Thus, a low sidelobe level is of primary interest for most applications, typical lower than -20 dB.

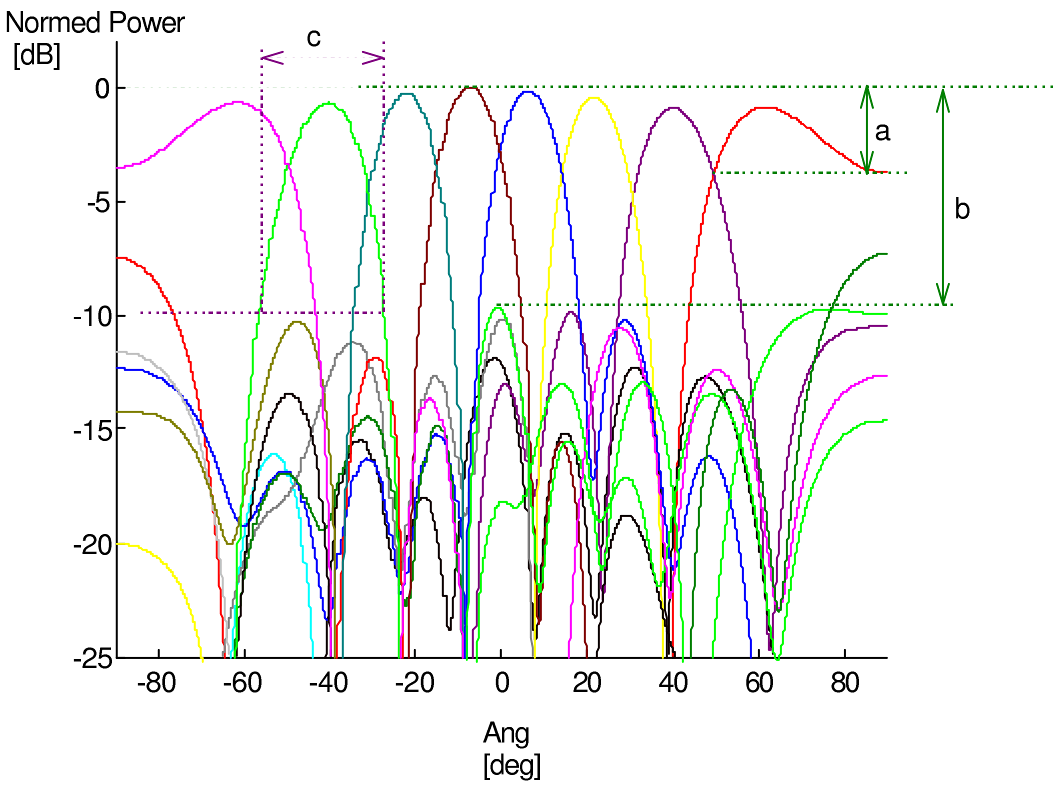

Figure 1.2: Typical antenna pattern from an array fed by a eight-element Butler matrix with the beams simultaneously illustrated, which shows crossover level (a), sidelobe level (b) and beamwidth (c).

Another parameter of interest is the width of the main beam at a certain power. It will be discussed later that it is possible to achieve lower sidelobes, but at the price of a broader beam. If the *beamwidth* is to large, more users would be covered by the main beam and then we are back where we started.

Many antenna requirements emphasise high gain with low sidelobes. Moreover, it is often important that the system has a high *beam crossover level*. The crossover level is shown in Figure 1.2 as the relative gain of either two adjacent beams at the point of intersection. This point is important, because it tells how much the antenna gain will vary over any angle covered by the antenna. For some applications, the crossover points of these adjacent beams are sometimes considered too low to provide enough gain at these angles, but it is not possible to simply crowd the pattern with a big number of different beams with any passive network without suffering *orthogonality loss*, as will be described in chapter 2.

1.3 Requirements for the Antenna Array

When one wishes to realise an antenna having a narrow beam, the number of elements are of particular interest. Hence, the higher the number of elements, the narrower will the main beam be, and the lower will the sidelobes become. Unfortunately, if the element number is increased, also the cost and the size of the antenna *and* the Butler matrix, which feeds the antenna, are increased. The size of the Butler matrix is particularly affected by the number of ports. For instance, a 8x8 Butler matrix needs 12 and a 16x16 Butler matrix calls for 32 hybrids. The optimum number of elements to achieve the pattern requirements, but to avoid suffering from cost and size, is eight in this case.

The implementation of the linear patch antenna is based on earlier work by Kuchar [A2]. However, that antenna was implemented with nine elements, but my antenna, connected to the Butler matrix, has to be an eight-elements antenna. Further on, studies showed that the two elements at each side of the array, which only have one neighbouring element, have different properties compared to the other ones with two neighbouring elements. But this problem can be decreased by adding a not excited second element at both sides, so called ”dummies”. Consequently, I have to implement a ten elements linear patch antenna.

Although the antenna is based on an earlier concept, new influences, such as mismatches and materials with other properties can change the performance of the antenna. A key feature of the quality of the antenna is the Voltage Standing Wave Ratio (VSWR). So the bandwidth of the antenna is defined as the frequency range where the VSWR[1] ≤ 2, which means that the antenna is properly matched. Thus, I shall have a VSWR≤ 2 for the operation frequency band.

1.4 General Requirements for the Butler Matrix

1.4.1 Microstrip Technique

The microstrip technique offers several advantages compared to other techniques (see Chapter 2.4.4) which have lead to increasing interest in microstrip circuits as parts in a microwave system. These merits, together with the fact that microstrip circuits are quite easy to manufacture, which made it possible for me to develop, manufacture and measure all of the components without any help from an external company, made the microstrip technique a suitable choice to implement the Butler matrix in.

1.4.2 Operating Frequency

The antenna is optimised for the unlicensed ISM-band at 2.45 GHz, which denotes the Industrial Scientific Medical - band. Hence, the rest of the system also has to be optimised for this frequency. The exact location of the frequency band is:

ISM-band: 2.400 MHz .... 2.483,5 MHz.

which gives that the wavelength λ_0 in space at 2.450 MHz is 120 mm

The requirements are not only that the system should work *somewhere* in the band. In fact, the system should cope with all requirements laid on the antenna pattern within the whole ISM- band.

[1] VSWR = 2 correspond to a retun loss of -9.54 dB.

1.4.3 Number of ports

As I explained above, the antenna has eight active elements and each output of the Butler matrix feeds one element. Consequently, the Butler matrix must comprise eight output ports.

Even though nothing really says that the Butler matrix then also must have eight inputs, this is the common way of design. (In general, it can have 2^n inputs and 2^n outputs [B8].) By letting the Butler matrix be made up of eight inputs, it is ideal to implement 90° hybrids in the structure. Otherwise, the same function of the Butler matrix could have been achieved by 180° hybrids or powerdividers with phaseshifters, but this would require some modifications of the signal flow in the structure.

Hence, eight inputs give the ability to attain eight different beams pointing at eight directions.

1.4.4 Maximum Size

Since the Butler matrix is manufactured completely in a 2-dimensional structure, the size of the Butler matrix could reach abnormal dimensions. The arguments that speak for a big structure is to avoid coupling between lines and components and the fact that a broadband-structure often is bigger compared to a narrow band component. On the other hand, a big Butler matrix does not only suffer from higher costs, the manufacturing process will become more difficult, which is especially true for me because I have only access to manufacturing equipment for circuit boards with limited size. The substrate I used has the dimensions 30x45 cm, and that is my limit.

One may find even this too big, but one should bear in mind what the purpose of the Butler matrix is: feed an *60 cm* long antenna. It is of low win to minimise the size of the Butler matrix when the dimension of the whole system will only be slightly affected.

1.5 Summary of General Requirements

- Butler matrix implemented in microstrip technique
- Operation frequency band: 2.400 MHz ... 2.483,5 MHz
- Sidelobes as low as possible. Lower than -20 dB is desirable
- Patch antenna array with ten elements
- Butler matrix with eight inputs and eight outputs, i. e. an 8x8 Butler matrix
- Crossover level < 5 dB
- Spacing between outputs of Butler matrix = 60.3 mm
  (To enable direct feed of the antenna elements)

- Maximum size of the Butler matrix < 30x45 cm
- 50Ω-system

1.6 Methodology Overview

Before one can go on with a large project, as a diploma thesis, one has to sit down and plan the schedule for the whole work so that the steps are taken in the right order and the requirements of one step is fulfilled before the next step can be made.

My strategy to achieve a working system consisting of an antenna and a Butler Matrix, was first of all to specify the general requirements for the antenna pattern. When this was done, I had to simulate the whole system to study the influences of the elements of the Butler matrix on the antenna pattern. From these simulations I derived the requirements for each component. When the requirements for each component were specified, I could go on and develop the components with the necessary performance. After having achieved suitable components, the next step was to implement a 4x4 Butler Matrix to check my predictions and to analyse if the elements worked together well. When the performance of the 4x4 Butler Matrix matched the simulations, I concluded that probably also the 8x8 Butler Matrix would work. After having manufactured the 8x8 Butler Matrix I could verify its performance by calculating the antenna pattern from the measured scattering matrix. The antenna could then be manufactured and it was verified that the resonant frequency was right. Finally the two parts were fixed to each other and the antenna pattern could be measured in a anechoic chamber.

1.7 Literature Overview

The relevant literature contributing to this thesis is listed in the bibliography section. This list is divided into three parts according to the subjects: Butler Matrix and Phased Arrays, Microstrip, and Patch Antennas.

The Butler matrix was first described by Butler 1960 [B1]. Other workers, notably Allen [B11] and Delaney [B12], have used the Butler matrix and published sketches of different matrices. Previous authors have published matrix designs, including precise values and location of all components, but Moody published 1964 [B5] a general systematic design procedure for a butler matrix regarding the values of the components and their location. A sketch of a 8x8 Butler matrix can be found in Lipsky [B2]. The source [B3] is a very comprehensive book about phased array antennas that has been intensively used in this work. Theoretical work by White [B6] and Stein [B7] deals with the degree of overlap and orthogonality of adjacent beams in a lossles networks. The connection between the Butler matrix and the FFT can be found in [B8] and [B9].

The next part in the bibliography is the literature in the field of microstrip design.[M7] , [M1] and [M3], but also [A2], have contributed with microwave theory and practical and theoretical information about the manufacturing. Many of the ideas regarding the design of the elements of the Butler matrix were found there. The theory behind the broad-band phaseshifter can be found in [M4] and [M5].

The last section contains relevant literature about the manufacturing of the patch antenna. Here the diploma thesis of Kuchar [A2] is the fundamental source for the manufacturing of the array. Supplementing theory about patch antennas can be found in [A2].

Chapter 2

Theory

This Chapter treats the theoretical background information about Butler Matrices and Phased Array Antennas so the reader should be able to understand this work. For further information see the references.

2.1 Phased Array Antennas

This section is intended to introduce the reader to the properties of antenna arrays and consists primarily of the practical results of array theory.

Array antennas consist of multiply stationary elements, which are fed by signal of appropriate phase and amplitude to enable a beam to be pointed at diiferent angles in space. They can be in a 2-dimensional structure, giving the ability to scan in both vertical and horizontal direction, or a linear array with the elements equally spaced in a line. This work used the latter one.

Each element of an array radiates a vector directional pattern that has both angle and radial dependence near the element. However, for distances very far from the element the *far field* dominates over the *near field,* and the radiation from the *i*th element can be written as

$$\mathbf{E}_i(\theta,\phi) = \mathbf{f}(\theta,\phi)\, exp(-jk_0R_i)/R_i \qquad (2.1)$$

The vector function of angle $\mathbf{f}(\theta, \phi)$ is called the element pattern and depends on the kind of element used. In general, the element factor is different for each element in the array, even for an array of equal elements; the difference is due to the interaction between elements, and is very sharp near the array edge.

The required distance R, so that one can safely use the far field approximation depends on the degree of fine structure desired in the antenna pattern. Thus, if really deep nulls or regions with extremely low sidelobe pattern have to be measured in the antenna pattern, it may be necessary to use

$$R = 10L^2/\lambda \qquad (2.2)$$

or a greater distance [B3]. Here L is the largest array dimension of the antenna and λ is the actual wavelength. A commonly used distance which is adequate for many pattern measurements is

$$R = 2L^2/\lambda \qquad (2.3)$$

For mine antenna with N = 8 pathces and with a element spacing of $d_x = \lambda_0/ 2$ will R according to equation (2.3) be

$$R = 2\,(8\,\lambda_0/2)^2/\,\lambda_0 = 3.84\text{ m} \tag{2.4}$$

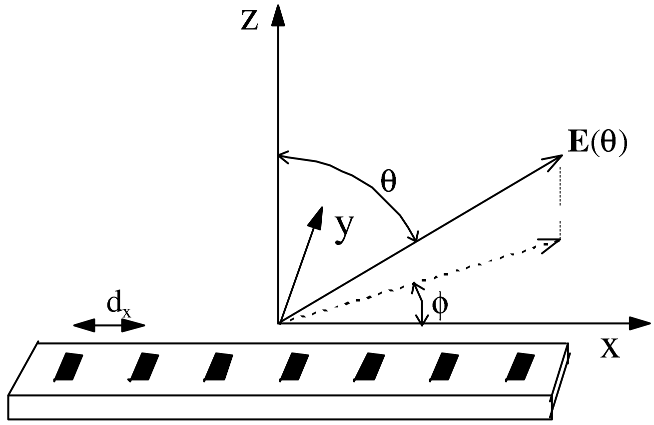

Figure 2.1: Array geometry for scanning in one plane

Figure 2.1 shows the geometry used in the analysis of a one dimensional array where

θ = the longitudinal angle on the unit sphere
φ = the latitude angle

These definitions will be kept through the whole thesis if not something other is told.

Consider an array of N elements arranged in a line as shown, with centre locations $x_n = nd_x$. The elements can be individual radiators as lines or patches. Under the assumption that all element patterns are the same, the *normalised* array radiation pattern in the far field is given at frequency f_0 by the summation over all N-elements as

$$\mathbf{E}\left(\theta,\phi\right) \;=\; \mathbf{f}\,(\theta,\phi)\sum a_n\,exp\left(jk_0\left(nd_x u\right)\right) \tag{2.5}$$

for $u = \sin(\theta)\cos(\phi)$ and with complex weights a_n of excitation assigned to each element. However, the actual system in the testbed utilises a linear array, which enables scanning in one dimension and gives $\phi = 0$. When the element factor is assumed the same for all elements the *array factor can* be written as

$$F\left(\theta\right) \;=\; \left|\sum a_n\,exp\left(jk_0\left(nd_x\,sin(\theta)\right)\right)\right| \tag{2.6}$$

At a fixed frequency can a maximum of F(θ) be created in the direction θ_0 by choosing the weights a_n to be

$$a_n = a_n exp(-jk_0 \, d_x \, n \, u_0)$$

(2.7)

which gives

$$F(\theta) = \sum |a_n| exp(jk_0 \, d_x \, n \, (u - u_0)) \tag{2.8}$$

where

$$u = \sin(\theta) \tag{2.9}$$
$$u_0 = \sin(\theta_0) \tag{2.10}$$

Consequently, Equation 2.2 shows that the array factor is a function of u - u_0. So, If u_0 given by Equation (2.10) is changed, the shape of the pattern is still unchanged at frequency f_0 in the variable u, the entire pattern is just displaced from the broadside pattern. This is a good reason for the use of the variable u and to plot the array pattern in the so called *sine-space.* This gives, that a beam pointing at a certain direction in space could be achieved by feeding the elements with the same amplitude, a *uniformly illumination*, but with a phase difference of u_0 between each element, .

In Figure 2.2 is the array factor of an array made up of eight elements spaced one-half wavelength apart plotted in the sine space at frequency f_0. The twa antenna patterns have both excitations with equal amplitude, but the phase between the antenna elements is different. The exitation with the main beam pointing at broadside has no phase difference but the other one has a phase difference of 67.5 degrees between the elements. From this figure it is obvius that the shape of the antenna pattern is independent of the variable u_0.

As a result of that the pattern is unchanged in sine space, the pattern will undergoes a broadening when it is plotted against θ. Consequently, a beam pointing at the broadside direction is the narrowest one, and broaden for directions far from broadside.

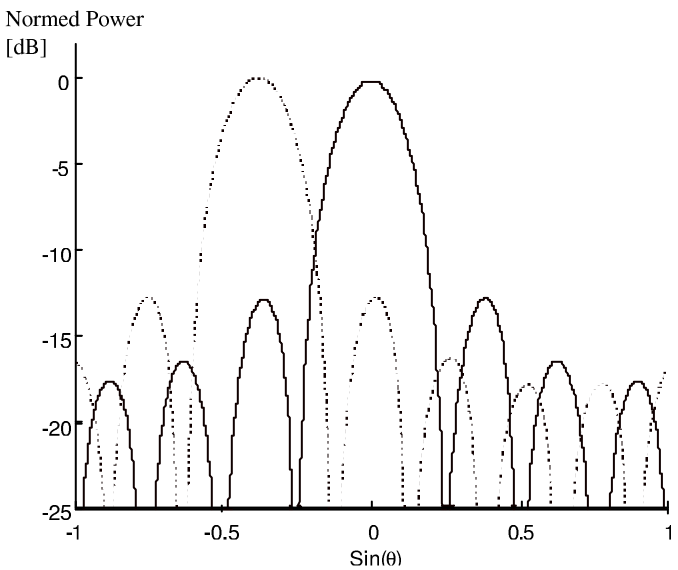

Figure 2.2: Radiation pattern from uniformly illuminated 8-element array with two kind of phase difference between the elements simultaneously

illustrated.

The main beamwidth at -3 dB for a uniformly illumination is the narrowest of any illumination, except for a special case of superdirectivity which is very difficult to realise practical. Also the *directivity* for a uniform illumination is the highest possible. Figure 2.2 shows also that a uniformly illuminated linear array gives a rather high level for the first sidelobes. But it is possible to achieve lower sidelobes if not a uniform illumination is used. Table 2.1 shows the variation of these features of the pattern for different amplitude distributions.

Amplitude distribution	**Half Power Beamwidth**	**Intensity of First Sidelobe**	**Gain Factor**
uniformly	$50.8\ \frac{\lambda}{l}$	-13.2 dB	1.0
cos	$68.8\ \frac{\lambda}{l}$	-23 dB	0.81
$\cos^2$	$83.2\ \frac{\lambda}{l}$	-32 dB	0.67

Table 2.1: Characteristic of line-source distribution. From [B3].

Notice here that the magnitude distribuition along the array is approximated with a continous line-source pattern. For a large array with the elements spaced a half wavelength or less apart has the illumination almost the shape of a countinous line. Hence, the line-source is a good approximation of the pattern for large arrays [B3]. Moreover, Table 2.1 gives that a illumination with lower sidelobes also gives a broader mainbeam and lower gain, which is the pattern directivity normalised to the maximum directivity of the line source.

It goes without saying that it is impossible to pick out the ultimate general illumination for an array. The choice of illumination depends on which requirements the antenna pattern has to cope with in the actual situation.

I want point out here, that according to Table 2.1 a uniform illumination not yields lower sidelobes than about -13 dB, but a cos-shaped illumination enables sidelobes lower than -20 dB.

2.2 Butler Matrix

2.2.1 Description/Use

The Butler matrix is a microwave network, normally employed in beam forming and scanning networks for linear and circular antenna arrays. This feed network typically takes the form of Figure 2.3, which is an *N* input and *N* output connection. But a Butler matrix could also have *n* inputs and *N* outputs. It consists of hybrid junctions and phase shifters and can be implemented with different microwave techniques such as waveguides, and as this Diploma thesis will show, in microstrip technique.

The main features of Butler matrices are:

- The Butler matrix has 2^n inputs and 2^n outputs.
- It has (N/2) $\log_2$ N hybrid junctions, where $N=2^n$
- The outputs are a fourier transform of the inputs
- The schematic of a Butler matrix is identical with the programming structure for the Fast Fourier Transform (FFT)

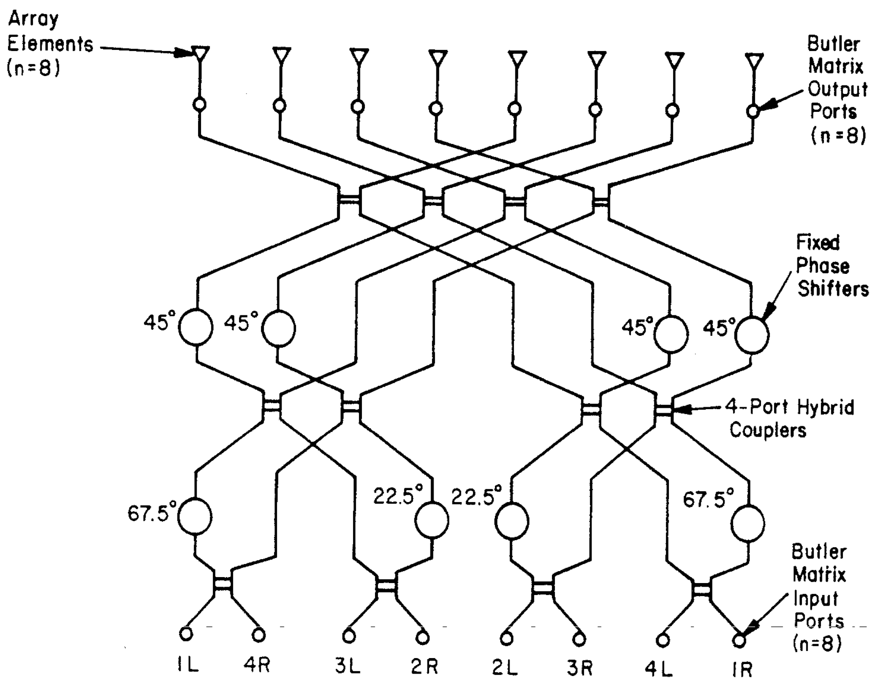

Figure 2.3: Eight-beam, eight-element Butler matrix

If a Butler matrix is connected to an array antenna, the matrix will act so that the array will have a *uniform amplitude distribution* and a *constant phase difference* between neighbouring elements:

$$\exp(-jknd_x u_i) \qquad (2.11)$$

for $u_i = (\lambda/Nd_x)i$. Where $i = \pm(1/2, 3/2, 5/2, ...)$ for N-even and $i = \pm(0, 1, 2, 3, ...)$ for N-odd.

This results in radiation at one of N different discrete directions covering a 180° angular sector of space (Figure 2.4). The actual direction of the beams depends of which one of the input the signal is introduced. The phase difference between radiating elements for a Butler matrix with N elements and for the pth beam location is given by

$$\Psi_n = \frac{2\pi d}{\lambda} \cos\alpha = \pm\frac{2p-1}{N} \times 180° \qquad (2.12)$$

Where the phase difference, Ψ_n, is plus or minus depending upon whether the beam is to right or left of broadside respectively. Because Equation 2.12 depends on λ will the beam angles u vary with fequency. The Butler matrix thus forms phase-steered beams which squint with frequency. The beam cluster is narrow for the highes frequency and broad for the lowest frequency.

If we letter each beam from the antenna with left (L) or right (R) to the direction of broadside, an 8x8 Butler matrix will get beams into the directions showed in Table 2.2.

	4L	**3L**	**2L**	**1L**	**1R**	**2R**	**3R**	**4R**
2.400 GHz	-65.0°	-40.4°	-22.9°	-7.4°	7.4°	22.9°	40.4°	65.0°
2.450 GHz	-62.7°	-39.9°	-22.4°	-7.3°	7.3°	22.4°	39.9°	62.7°
2.485 GHz	-61.0°	-38.7°	-22.0°	-7.2°	7.2°	22.0°	38.7°	61.0°

Table 2.2: Beamdirections for an eight-elements antenna array fed by a 8x8 Butler matrix within the ISM-Band.

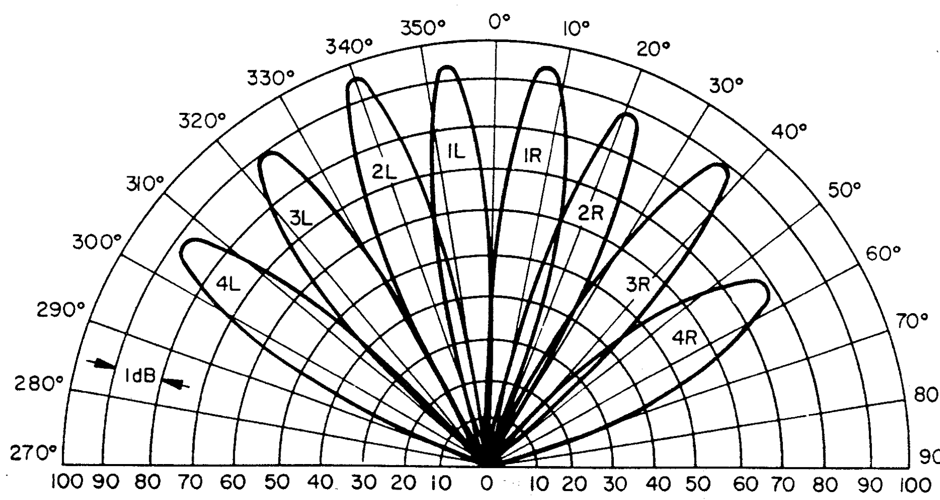

Figure 2.4: Simultaneous eight-beam radiation pattern fed by an 8x8 Butler matrix using one input port at the time. From [B3].

2.2.2 FFT and the Butler Matrix

It is probably impossible to determine who first realised the similarity between FFT and Butler matrices. The fact is, that the Butler matrix already had existed a few years before FFT appeared in 1965, and in the same year Wishner noted the similarity on a seminar [B13].

There are minor differences in the details of the flow diagram when the FFT algorithm is implemented on a computer compared to the signal processing of a Butler matrix. The problem of computing the sampled Fourier transform of a function is thus equivalent to the problem of computing the output signals from a Butler matrix, given the input signals.

2.3 Orthogonal Beams and Superposition of Beams

2.3.1 Superposition of Beams

When the signal is restricted to enter only one of the input ports of the Butler matrix at a time, we get (unfortunately) an equal amplitude illumination across the array which gives rather high sidelobes (about - 13 dB). But it is possible to achieve lower sidelobes by superposition of several beams. As mentioned above, a cosine or cosine-squared illumination obtains better performance of the sidelobes. From the expression

$$\cos\theta = \frac{e^{i\theta} + e^{-i\theta}}{2} \qquad (2.13)$$

it is obvious that a cosine-tapered illumination can be regarded as the superposition of two uniform illuminations having a progressive phase shifts relative each other. This is shown in [B3]. Consider input ports i and j that form the array excitations $\exp(-jknd_x u_i)$ and $\exp(-jknd_x u_j)$ for

$$u = p\lambda/(Nd_x) \qquad (2.14)$$

for integer p, where N are the numbers of elements and d_x is the element spacing. Setting $j = i+1$ and $u_j = u_i + \delta$ gives a superimposing of two adjacent beams:

$$\exp(-jknd_x u_i) + \exp(-jknd_x u_j) = 2\exp(-jknd_x(u_i + \delta/2))\cos(knd_x\delta/2) \qquad (2.15)$$

Here we see that the beam angle is in the middle of the two beams and that the amplitudes at the elements have a cosine dependence. Similarly, a cosine-squared illumination can be regarded as the superposition of three uniform illuminations and so on. But the cosine-squared illumination does not represent the most efficient method of superposing three uniform illuminations for control of sidelobes. By giving an excitation like $\cos^2(nkd_x\delta/2) + c$, usually known as a cosine-squared on a pedestal function, the pedestal height could be varied to produce the best pattern. With a pedestal height of 0.08 it is possible for the pattern sidelobes to reach -43 dB, according to [B3].

One of the facts that does not speak for a tough reduction of sidelobes due to superposition of beams, is that it also gives a considerably increase in beamwidth. White presented in his article [B6] how that the price for low pattern sidelobes is a larger beamwidth, which can be seen in Figure 2.5.

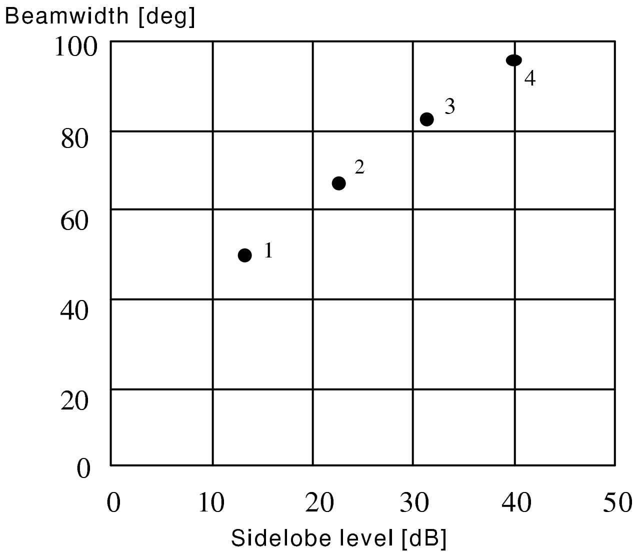

Figure 2.5: Beamwidth vs Sidelobe level. From [B6].

1) Uniform illumination
2) Cosine illumination
3) Cosine-squared illumination
4) Cosine-cubed illumination

But this is not the end of the story. It is not only the beamwidth that suffers from superposition of beams. The *orthogonal* feature of the beams are also affected.

2.3.2 Orthogonal Beams

The feature of orthogonal beams is of particular interest if one wants to radiate several beams simultaneously. The field of orthogonal beams is rather theoretical and not all steps in the mathematics will be shown. If more information is wished, I can refer to [B3],[B6] and [B7], where deeper analysis are performed.

In many applications, it is desirable to radiate several independent beams simultaneously from an array. That is, the radiation resulting from a simultaneous excitation of two or more inputs ports should be a simple linear superposition of the radiation obtained when the ports are excited separately. Additionally, an applied power to one of the input ports should cause no influence to any of the other ports. For the most cases it is also desirable that the antenna and the feednet are completely made up of passive components for reasons of equipment simplicity. (As the antenna and Butler matrix in this work). The losses should also be kept low, so ideally the feednet should be lossless.

In other words, a requirement that the antenna and the feednet should be both lossless and passive is equivalent to a requirement that the radiated power should be strictly equal to the input power. But White[B6] and Stein [B7] showed that this could only be achieved if *the beams are orthogonal in space* That is, the orthogonalitiy relation

$$\int_{0}^{2\pi} d\theta \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} F_j(\theta,\phi)\, F_k^*(\theta,\phi)\, cos\phi \;\; d\phi \;\; = \;\; 0 \qquad (2.16)$$

where

$F_j(\theta,\phi)$ = the radiation patter associated with the jth input port
$F_k^*(\theta,\phi)$ = the complex conjugate of $F_k(\theta,\phi)$

has to be fulfilled. This conclusion is based on conservation of energy relations and is independent of the the typeof antenna involved. Stein [B7] has derived the conditions for maximum efficiency from multiple-beam networks using the scattering matrix of the feed network according to the relation

$$y_k \;=\; \sum_{m=1}^{M} \mathbf{S}_{km}\mathbf{x}_m \qquad \text{or} \qquad \mathbf{y} \;=\; \mathbf{S}\mathbf{x} \qquad ....(2.17)$$

where $\mathbf{S}_{km}$ is the scattering matrix and $\mathbf{x}$ is the input vector and $\mathbf{y}$ is the output vector of the feed network. And by studying the pattern and the beam overlap he came to the far-reaching conclusion that the normalised power transmitted through the network is less than or equal to the inverse of the maximum eigenvalue of the overlap of the beams in space [B7. That is, if the efficiency of the system is plotted against $u \;=\; 2\lambda/d_x$ which is termed the *interbeam spacing*, we will find that the efficiency depends on the interbeam spacing. Hence, the beams are orthogonal when the interbeam spacing is a number. So, if there is a set of nonorthogonal beams, the interbeam spacing could be increased until they are orthogonal . But if the interbeam spacing is increased, the beams are ”moved” away from each other, and the crossover level is lowered. Thus, *the radiation pattern and crossover levels cannot be specified independently.* In most cases leads requirement for low-sidelobes leads either to low radiation efficiency and high crossover levels, or increased spacing and low crossover levels with improved efficiency. Of course, the final system will be a tradeoff between these two extremes.

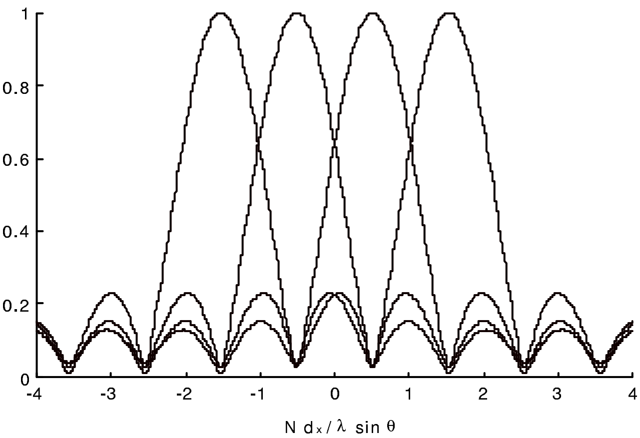

Figure 2.6: Four beams simultaneous from an array fed by a Butler matrix.
The beams are normalised to show the orthogonal nature.

For instance, consider the beams from an equally illuminated array visualised in Figure 2,6. These beams are excited from an array fed by a Butler matrix using one input port. Hence giving an uniform illumination. The pattern from this kind of illumination is often referred as sin *x*/*x*, because the beams are actually shaped this way. An integral over any number of these pattern periods exhibit orthogonality. Thus the beams created from a Butler matrix using one input port are orthogonal in space. Consequently there are no problems to simultaneously radiate two beams, or all eight, from a 8x8 Butler matrix without suffering from losses. A problem arise instead when the designer wants to use a set of, for instance, cosine illuminated beams. If one single beam of this type at a time is radiated by means of using two input ports of the Butler matrix, there is no problem with orthogonality beacause there are no beams to be non orthogonal to. However, If two beams with cosine amplitude distribution are simultaneously radiated, the beams would only be orthogonal if the interbeam space is $2\lambda/d_x$ but this would correspond to a crossover level of -9.5 dB, which is to consider as too much..

2.4 Microstrip Lines

2.4.1 Description

A microstrip structure consists of a shaped layer of metal on one side of a thin sheet of dielectric material which is completely covered with metal on the other side. The shaped metal layer on the frontside is often printed, and could act as a circuit or an antenna. The metal, usually copper, is very thin, about some micrometers. The dielectric material, termed substrate, is the mechanical backbone of the microstrip circuit. The substrate is made of low-loss material, and its permittivity and thickness determine the electrical characteristics of the circuit or of the antenna.

The complete metal layer on the other side of the substrate is grounded and hence called *ground plane*. A main condition is that the frequency used should enable the components to have dimensions in the same order as the wavelength. Thus, microstrip is ideal for frequency ranging from 0.5 to 10 GHz.

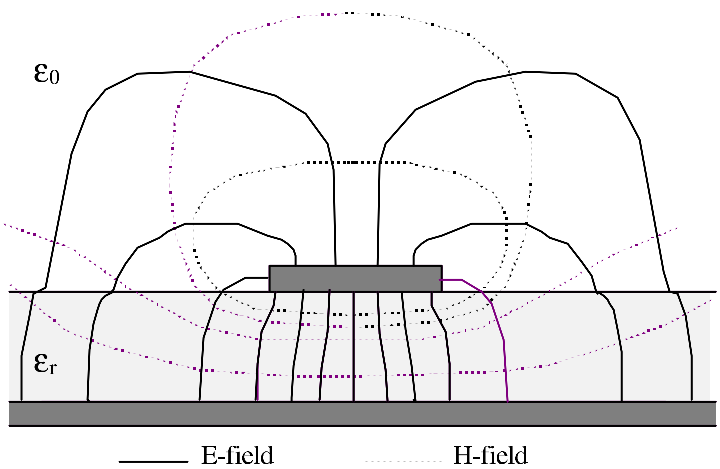

Figure 2.7: The electromagnetic field around a microstrip.

Due to the inhomogeneous nature of microstrip circuits (Figure 2.7), they are quite difficult to analyse. Their analysis was carried out by Wheeler, who made use of a quasi-TEM approximation and conformal mapping [A1].

2.4.2 Waves on Microstrips

There are three distinct categories of waves with quite different behaviours that occur in a microstrip structure. The behaviour of these waves are depending on in which direction they are transmitted in the substrate:

Space Waves

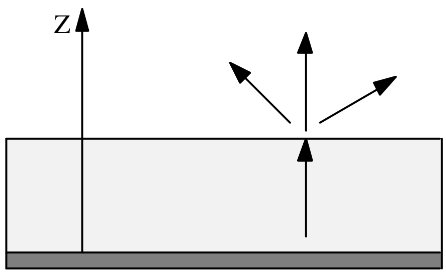

Figure 2.8: Space waves in a substrate

First of all, if the direction of the waves are upwards, with elevation angles θ between 0 and π/2, they move towards the free space where they do not find any further interfaces (Figure 2.8). The result is a radiated wave, with the power decreasing as $1/r^2$. This phenomena is just what is wanted for an antenna, which specifically relies on radiation for its operation. However the same category of waves is found as seroius leakage in transmission lines and circuits, which of course is undesirable.

Surface waves

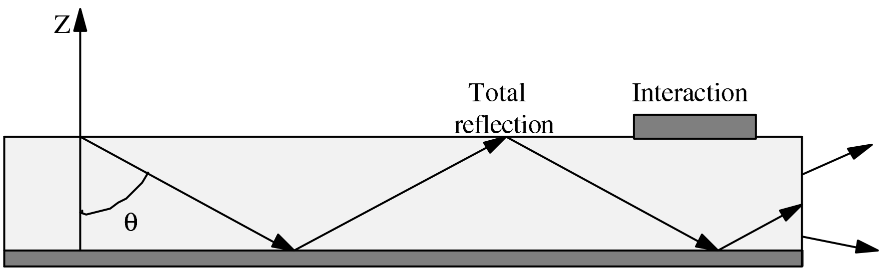

Figure 2.9: The transmission of surface waves in a substrate

If the direction of the waves is slightly downward, with elevation angles θ between 0 and π - arcsin($1/\sqrt{\varepsilon_r}$), the waves are reflected by the dielectric-to-air boundary (total reflection condition).

As the waves also are reflected by the groundplane, they are trapped between these two boundaries. Surface waves occur with a power decrease of only about 1/r. The surfaces waves lead to a decrease of the antenna efficiency, since some of the signal's energy does not reach the intended user. What is even poorer, the surface waves also introduce spurious coupling between different element mounted on the same substrate. This effect mostly effect the performance to the negative for circuits and antennas, so their excitation should be suppressed.

Guide waves

If a metal layer is added locally on top of the substrate, an additional reflecting boundary is introduced, and the waves bounce back and forth on the metal boundaries. The waves between the metal layer can only exist for some particular values of the angle of incidence, and a discrete set of waveguide modes is formed. The metallic layers which guide the waves, waveguides, can easily be given an appropriate shape due to printed circuits. The wave guide mode provides the normal operation of all transmission lines and circuits.

2.4.3 Difference between Circuit and Antenna Requirements

We have concluded that two different kinds of waves are favourable for transmission lines and antennas. Space waves for antennas and guided waves for transmission lines. The question that arises is, can we get an efficient antenna and a non radiating microstrip circuit *on the same substrate*. The answer is no. As can be seen in Table 2.3 the requirements for circuits and those for antennas are contradictory. When combining the two functions, for instance if the feed lines are wanted to be located at the same level as the radiating patches in an antenna, some kind of compromise must be made between transmission and radiation. The resulting design cannot be optimalum for both functions.

The electromagnetic field in a transmission line or in a circuit must remain concentrated in the close vicinity of the conductors so that only guided waves may be excited. Therefore such a circuit is printed an a thin substrate of a large permittivity dielectric material so that the guided waves become predominant. In the antenna, on the other hand, the radiated waves are favoured when the substrate is thick and has a low permittivity. The surface waves, which mostly cause a lot of trouble, becomes significant when the substrate is thick and has a large permittivity. Thus gives the most unwanted combination of substrate thickness and permittivity for a designer.

Permittivy	**Substrate type**	
ε_r	**thin**	**thick**
small		Antennas
Large	Lines and Circuits	Surface Waves

Table 2.3: Circuit and Antenna Requirements

2.4.4 Advantages of Microstrip Circuits

There are a lot of merits that have made microstrip circuits an alternate approach to cumbersome waveguide. The most important ones are listed below:

- **Low cost**
  Microstrip circuits are very well suited to be manufactured in large quantities, leading to a low cost per unit.

- **Low weight and volume**
  Compared to waveguide circuits that consist of mechanical devices and sections of metal tubes bolted together, microstrip circuits are outstanding regarding weight and volume.

- **Complete circuit on a substrate**
  One of the weak links in any assembly of electronic circuits is the need for rigid and permanent connections and transitions of the components. Microstrip circuits offer here a reliable way because the components of the circuit are realised directly on the substrate and need not to be solded onto it.

- **Suitable for insertion of MIC (Microwave Integrated Circuits)**
  Microstrips open structure make it possible to easily insert a MIC into the circuit by only using solder. Compare this with waveguides or a stripline, which require a major operation.

2.4.5 Drawbacks of Microstrip Circuits

The easy layout of micostrips circuits has also given them some specific problem, in that they require particular care in the design and fabrication. You may call them drawbacks.

- **Hard to analyse**
  The microstrip structure with groundplane-substrate-metal-air are inhomogenous. This leads to big problems when one has to solve Maxwell´s equations. Actually, all analysis are performed through approximations, requiring considerable time if they should be accurate. By using modern microwave simulation software, this drawback can easily be overcome

- **Difficult to adjust when manufactured**
  When a microstrip circuit is printed and needs to be tuned, adjustments are difficult or impossible. This is a major drawback which means that you have to build a new circuit if you find that the circuit does not work.

- **Limitation in Frequency**
  There is a limit for small dimensions of substrate and lines, giving a limit at

millimeterwaves. Conversely, if waves are too long this leads to large and bulky circuits.

- **Restricted two-dimensional layout**
  The two-dimensional structure of microstrip circuits leads sometimes to problems, for instance, when the designer wants to cross two lines with each other. This could be solved by multilayer structures, but this is not always possible and vias need why good modellings to get reproducable results.

- **Effected by enclosure**
  The open unshielded structure of microstrip circuit needs special care,.when they have to be enclosured so that the electromagnetic fields above the circuit are not disturbed.

Chapter 3

Simulation Setup

3.1 Needs for Simulations

When a designer has to develop a system, there are usually a lot of requirements which must, or should be, achieved. Often all of the requirements cannot be met at the same time and the designer has to decide which of the demands he should stand up to in order to reach the best result. A way to investigate the features of a system in order to be able to make a statement about the optimum solution is to perform analysis. As many systems are not trivial enough to be analysed analytically, the designer has to perform a *numerical simulation* of the system.

The question in this work that needs to be answered is, how different features of the *elements* of the Butler matrix affect the antenna pattern. From this the appropriate elements of the Butler matrix can be chosen for the implementation.

Due to the relatively complex structure of the Butler matrix it is hard to carry out a simple analysis of the signal flow in the system, from which it can be derived how system performance is affected by different elements. Therefore, I decided to use the computer program MATLAB to simulate the signal flow in the Butler matrix under different scenarios.

3.2 About MATLAB

The computer program MATLAB was used for the simulation of the Butler Matrix and the prediction of the pattern characteristics. MATLAB is a simulation tool with a programming language like interface. The user implements his own programs in a way close to a language as C or Fortran. However, MATLAB is especially adapted to numeric calculations. The major merit of MATLAB is that the basic data element is a matrix that does not require dimensioning. By using matrix formulations the problems that arise in this work could be solved in a fraction of the time it would take in a language such as Fortran, Basic, or C, where you do not have such extensive support for matrix calculations.

MATLAB (MATrix LABoratory) was originally written by Cleve Moler, and has since then evolved over a period of years with input from many users. MATLAB is today a high-performance interactive package for scientific and engineering numeric computation.

3.3 Setup of the simulations of the Butler Matrix

3.3.1 Modelling the Structure

First of all I would like to state the demands for the simulation setup. My simulation should be able to calculate the actual antenna pattern from a signal entering an input port and visualise it with the relevant information of the characteristics of the pattern. Further on, all the elements of the Butler matrix that have an influence on the signal flow through the structure should be modelled with realistic properties according to the ideal performance and should be supplemented with permanent and random errors. The interface should enable easy change of the properties of the elements, so that different scenarios can be compared.

The property of the Butler matrix as a passive network, where one signal introduced into one input port gives signals out of all output ports without the help of active circuits, makes it very suitable for describing it with a scattering matrix (Equation 2.17). Thus, it is possible to see an 8x8 Butler matrix as a sixteen-port. If the analysis is restricted to investigate eight of the ports as input ports where signals are introduced, and does not take into account the signals coming out from these ports, we do not need to define a 16x16 elements-matrix, but we can define a 8x8 transmission matrix $\mathbf{T}$. If the vector $\mathbf{x}$ contains the signals introduced into the input ports and $\mathbf{y}$ is a vector containing the signals from the output ports the equation for $\mathbf{y}$ is

$$\mathbf{y} = \mathbf{T}\mathbf{x} \tag{3.1}$$

where $\mathbf{T}_{km}$ has eight rows and eight columns.

In the theoretic structure (Figure 2.3) the Butler matrix comprises two elements: Hybrids and phaseshifters. But in the practical case some more appear. In a planar microstrip structure the problem of two crossing microstrip lines arises. This can be solved by the designer in different ways, but anyhow the solution differs from the ideal characteristic of a microstrip line and reflections and phase shifts are introduced which affect the signal flow and consequently the antenna pattern. Furthermore, the microstrip line in the Butler matrix must sometimes perform a bend, which also, how small they ever seem to be, gives reflections in the net.

The implementation in microstrip technique gives also some more influences. One of the most significant problems when integrating many circuit elements on the same board is the isolation between circuits, or the isolation across any given circuit. Moreover, in an implementation the parameters of the structure are not the same everywhere. For instance the height of the substrate could differ from one point to another, as well as the permittivity. The manufacturing process gives also variations of the width of the striplines, which of course affects the properties of the circuit.

The influences from these errors are hard to tell and considerably difficult to simulate exactly. One way of getting around the problem is to introduce these influences as random errors. Hence, because the errors appear randomly, what could be easier than to model this influence by adding a random error to the overall performance of each element of the Butler matrix?

By looking upon the elements in the simulation of the Butler matrix as either four- or two-ports with a transmission matrix gives a lot of interesting features. Firstly, if an element is developed and measured, the measured data of the scattering matrix can directly be used for the transmission matrix in the simulation. Secondly, this gives a high accuracy and the ability to easily change to new data from the measurements. Thirdly, the design of the Butler matrix will become much easier. The Butler matrix now consists of a pair of different kinds of connected elements with verified features. The development of the 8x8 Butler matrix can now be simplified according to the following schedule.

1. Develop and measure different kind of elements
2. Simulate the 8x8 Butler matrix with the measured data from the elements with added errors from random faults in the structure.
3. Choose the elements that give the best performance with respect to the requirements.
4. Implement and measure a 4x4 Butler matrix with the actual elements.
5. Calculate the antenna pattern from the 4x4 Butler matrix.
6. Change the random errors of the elements in the 4x4 simulation so that the same pattern as the measured is achieved.
7. Make a new simulation for the 8x8 Butler matrix with the new random errors.
8. Investigate if the requirements regarding the antenna pattern are reached.
9. If result is OK: implement a 8x8 Butler matrix with the actual elements.
   Else: Go back to point 1.

3.3.2 Simulation of the Elements

In the simulation, the Butler matrix is regarded as consisting of two- or four-ports. But which parts of the structure that influence the performance should be regarded as elements and which should be treated as random errors. The hybrid and the phaseshifters definitely fall into the first category, as well as the crossover. The bends on the other hand, depend to a great deal on how the final microstrip lines are orientated in the substrate and how the layout of the net looks like. This is quite difficult to answer at this stage. Furthermore, the influences of the bends are small compared to other influences, as for example coupling, so the bends should, as well as the coupling, be treated as random or added errors.

To sum up. The crossovers and the hybrids are to be seen as four-ports and the phaseshifters as two-ports. The rest of the influences on the signal flow in the Butler matrix are simulated as random errors. The structure of the Butler matrix in the simulation is shown in Figure 3.1.

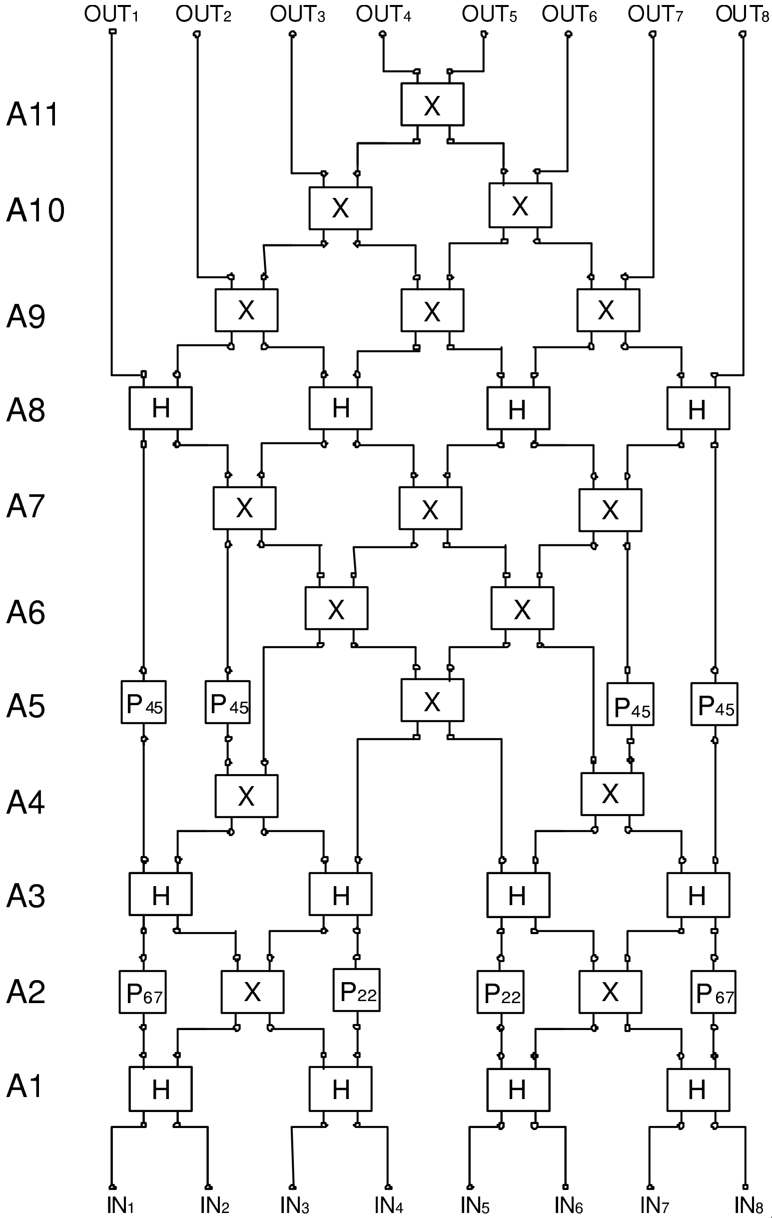

Figure 3.1: The Butler matrix dived into four- and two-ports.
Compare with Figure 2.3.

The next step is to find an appropriate form for the elements in the transmission matrix, which could meet all the demands of flexibility and physical relevance. This could be achieved by writing each element in the transmission matrix as

$$T_{\mathrm{km}} = T_{kmi}\left(1+\delta_{kmm}+\delta_{kmr}\right)\exp\left(-j\left(\varphi_{kmi}+\varphi_{kmm}+\varphi_{kmr}\right)\right) \tag{3.2}$$

where T_{kmi} is the ideal absolute value of the element, whereas δ_{kmm} and δ_{kmr} are the relative errors with respect to measured data and random errors. The ideal phase is denoted φ_{km_i} and phase errors according to measured and random errors are provided by φ_{km_m} and φ_{km_r}.

How to calculate the parameter describing the difference between the measured value and the ideal one of the elements is obvious, but the simulation of the errors which appear with random probability needs deeper investigation. The random error is modelled either to have a normal distribution or to be equally distributed. For instance, the transmission value for the hybrids between two ports is 3dB. When a random error appears, the transmission value could either get lower or higher. The fluctuations around the ideal value is in this case set to occur with the probability of a normal distribution. In another case when there is a signal transmitted in a direction where it ideally should not be any, for example coupling in a crossover, it is difficult to tell which *phase* this signal will come out with. The phase could be anything between zero and 2π with the same probability, hence a rectangular distribution is used.

Under certain circumstances the random errors are treated as the absolute value of the normal distribution. This occurs for instance when the errors are a transmission in a direction where it should be zero, as in the example above for the crossover. The transmission coefficient has to be somewhere between zero and one, but it is surely closer to zero than one. This case is modelled by adding an error that appears with the *absolute* value of the normal distribution. In this way all of the elements in the transmission matrix are adapted for each type of component to suite the behaviour of the structure in a realistic manner.

In the simulation program these errors can be set with appropriate strength to enable a fast change from one situation to another. When the simulation enables random errors, each component of the Butler matrix gets its individual transmission matrix which is stored through out the calculations.

3.4 Algorithms for Simulations

In order to determine the transmission matrix of the Butler matrix in Equation 3.1, different algorithms have been investigated. These are presented below.

In an ideal Butler matrix all the signals are transmitted in the direction from input to output ports and no signals are travelling in the other direction (see Figure 3.2). But that is only true in theory. In a real circuit is it almost impossible not to have reflections when a signal is introduced to a element and not to get coupling between two ports. As a result a part of the signal is reflected back again in the direction of the input ports, which gives that some energy of the signal does not reach the output ports. Moreover, the signals travelling in the backdirection could once again be reflected or undergo any other nonideal transmission which would affect the signal flow in the structure.

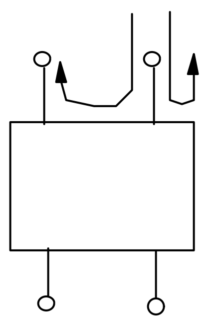

Figure 3.2: Example of nonideal transmission for a four-port which gives signals travelling in the opposite direction compared to the ideal one.

3.4.1 Direct Algorithm

If the reflections and the nonideal transmissions which cause signals travelling in the back direction are neglected, a much more easily analysed signal flow appears. The elements of the Butler matrix can be divided into eleven rows. The signals into the rows can thus consist of eight signals, as shown in Figure 3.1. As a result, the signals can be implemented as vectors and the elements as matrices. Hence, the vector containing the signals between row k and $k+1$ is denoted $\mathbf{x}_\mathrm{k}$, giving that the input vector is $\mathbf{x}_0$ and the vector for the signals at the output ports to be $\mathbf{x}_{13}$. The modification of the signals, when the signals are passing through an element, can be achieved with a matrix now. Thus, the equation that relates signal vector $\mathbf{x}_{k-1}$ to signal vector $\mathbf{x}_k$ can simply be written as

$$\mathbf{x}_k = \mathbf{A}_k \, \mathbf{x}_{k-1} \tag{3.3}$$

where $\mathbf{A}_\mathrm{k}$ has eight rows and eight columns.

For instance, watch row number five (A_5) in Figure 3.1. This row of elements consists of four 45 degrees phaseshifters, two microstrip lines just passing through, and a crossover. The matrix for this row is

$$\mathbf{A}_5 = \begin{bmatrix} T_{45_{21}} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & T_{45_{21}} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & T_{strip} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & T_{x_{21}} & T_{x_{24}} & 0 & 0 & 0 \\ 0 & 0 & 0 & T_{x_{13}} & T_{x_{34}} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & T_{strip} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & T_{45_{21}} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & T_{45_{21}} \end{bmatrix} \tag{3.4}$$

where T denotes the value of the transmission matrix for the actual element between the respective ports.

In the ideal case the matrix in complex representation is equal to:

$$\mathbf{A}_5 = \begin{bmatrix} e^{-j45°} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & e^{-j45°} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & e^{-j45°} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & e^{-j45°} \end{bmatrix} \tag{3.5}$$

Here some features are obvious. The diagonal elements in the transmission matrix for the crossover vanish because no transmission is allowed between these ports and all of the signal is transferred to the opposite port. This gives a switch of the positions of the signals in the vector, like the signals switch their places by a physical crossover. The signals introduced to the phaseshifters keep their positions in the vector but are phase shifted by 45 degrees. Where the elements are just microstrip lines, the signals do not change, and this gives the number one on the diagonal. In a similar manner all of the rows of the Butler matrix are converted into matrices.

Thus the relation between the introduced signals to the Butler matrix and the outputs can be expressed as:

$$\mathbf{x}_{13} = \mathbf{A}_{13}\mathbf{A}_{12}\mathbf{A}_{11}\mathbf{A}_{10}\mathbf{A}_{9}\mathbf{A}_{8}\mathbf{A}_{7}\mathbf{A}_{6}\mathbf{A}_{5}\mathbf{A}_{4}\mathbf{A}_{3}\mathbf{A}_{2}\mathbf{A}_{1}\mathbf{x}_{\mathbf{0}} \qquad (3.6)$$

Hence, the result can be obtained by matrix multiplication between all of the element matrices of the Butler matrix, which is the reason, why I have chosen to call this method the 'direct algorithm'.

3.4.2 Recursive Algorithm

The major drawback of the direct method is that it does not take the reflections into account. In order to investigate the accuracy of the direct method, I have performed simulations with a second method. This method relies on an recursive algorithm which takes into account multiple reflections in the structure of the Butler matrix.

The idea is to add the contributions from all possible ways, a signal can go from the input to the output port. To do this we use the transmission matrix $\mathbf{T}$ with the elements T_{km}. The algorithm is based on the observation that the transmitted signal from an element to an output port in the structure, is equal to the transmission from multiplied with the transmission matrix of the element. Thus is the Butler matrix in the program implemented as the structure in Figure 3.3.

The recursive algorithm is best described with the following example:

1. The question to answer is, how much of the signal entering the port i in the element n is transmitted to the final port k.

2. Imagine that a two-port is denoted with 6

3. It is connected to element 2 and 12

4. Suppose that the signal $T_{6,1}$ is introduced into port 1 of element 6.

5. The part of the signal that goes from 1 to port 2 is described by the transmission element S_{21}. Hence, the signal that goes from port 1 to port 2 is equal to $T_{6,1}\,S_{21}$..

6. Consequently, the signal that is reflected back is described by $T_{6,1}\,S_{11}$

7. Therefore, the transmission to port 1 is divided as

$$T_{6,1} = T_{6,1}\,S_{21} + T_{6,1}\,S_{11}. \qquad (3.7)$$

8. But$T_{6,1}\,S_{21}$ is the same as the transmitted signal to element 12, i.e. $T_{12,4}$ and $T_{6,1}\,S_{11}$ is the same as $T_{2,3}$.

9. The recursion is terminated when a port with a known transmission is reached.
    - the output port is reached ⇒ return 1
    - the inputs or outputs of the Butler matrix nonequal to port *k* is reached. ⇒ return 0
    - the transmitted value is lower than a chosen accuracy. ⇒ return 0

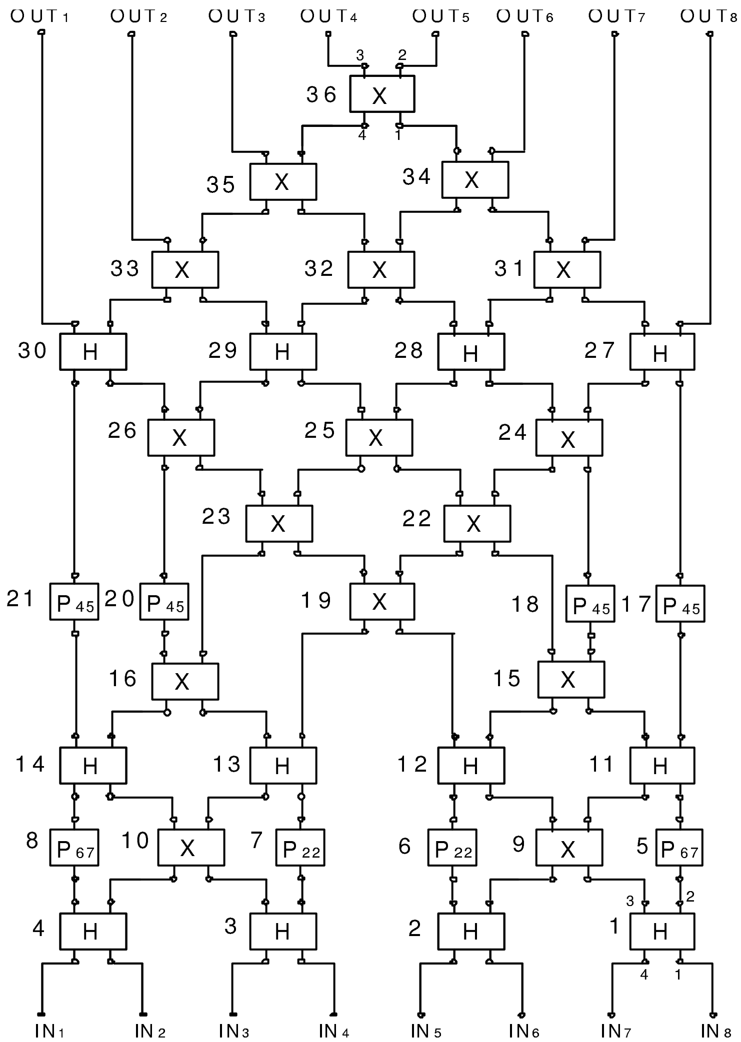

Figure 3.3: Structure of the Butler matrix for the recursive method.

3.5 Comparison between the Direct and the Recursive Algorithm

Both of the methods have their merits and drawbacks.

- The direct method enables fast calculations but does not compensate for single or multiple reflections.
- The recursive algorithm provides high accuracy calculations but requires much more calculations, which require a lot of time for one simulation to be accomplished.

The use of the recursive method for the simulations showed, that it was so timedemanding that it could not be used for frequent simulations. The simulations have to be put through with the direct method, but the recursive method could provide a comparison of the accuracy for the direct one. Therefore, the transmission between an input port to an output port of the Butler matrix was investigated with both methods to give a hint of how much the influence of the reflections could be.

In this simulation the scattering matrix was made up of measured data from real implemented elements, but with no correction for random errors which would make a comparison impossible between the two. On the other hand, the scattering matrices were set to be somewhat pessimistic compared to the measured data. But on the whole, this is a realistic simulation of the Butler matrix.

First of all the transmission was predicted from one input to an output with the direct method. After this was done, a serie of simulations were accomplished for the recursive method with different values of accuracy. The accuracy ε determines when the recursion should be terminated. A value of ε equal to 0.1 says that transmission lower than this should be omitted.

ε	**Recursive**	**Direct**	**error**
$1\cdot10^{-1}$	0.2992 -0.1522i	0.2810 -0.1578i	0.0134
$5\cdot10^{-2}$	0.2922 -0.1522i	”	0.0072
$1\cdot10^{-2}$	0.2929 -0.1565i	”	0.0098
$5\cdot10^{-3}$	0.2927 -0.1570i	”	0.0100
$1\cdot10^{-3}$	0.2701 -0.1791i	”	0.0018
$5\cdot10^{-4}$	0.2701 -0.1908i	”	0.0084
$1\cdot10^{-4}$	0.2798 -0.1979i	”	0.0204
$5\cdot10^{-5}$	0.2800 -0.1980i	”	0.0206
$1\cdot10^{-5}$	0.2796 -0.1986i	”	0.0207
$5\cdot10^{-6}$	0.2790 -0.1995i	”	0.0207

Table 3.1: Comparison between simulations with the recursive and direct method.

As shown in Table 3.1, the scattered value converges to a certain value when the accuracy is increased. It is also obvious that the direct method does not compensate for the multiple scatterings in the same way as the recursive method with high accuracy. But with this comparison at hand a value could be determined, by which the random errors have to be increased to achieve the same influence.

Chapter 4

Implementation of Elements

4.1 Substrate Material

The Butler matrix is developed and implemented on a RO4003™ substrate with technical parameters according to Table 4.1. Also the feed lines of the patch antenna were implemented on this substrate. RO4003TM[4] is a woven glass reinforced, ceramic filled material that was developed to provide high frequency performance for reasonable prices. Both sides of the substrate are covered with a thin layer of copper.

Property	RO4003™
Thickness	0.81 ± 0.04 mm
Relative Permittivity	3.38 ± 0.02
Dissipation factor	0.002

Table 4.1: Technical data for substrate RO4003™

Some fact of use: an 50 Ohm transmission line has a width of about 1.8 mm on this substrate and the wavelength λ at 2.45 GHz for a line of the same width is 72 mm.

4.2 Software and Manufacturing Process

4.2.1 Manufacturing process

All of the basic microstrip components were developed and manufactured at TU-Wien using photoetching techniques. The design flow from simulation to the final product is as follows. First of all are the structure designed simulated and optimised in the program Microwave Harmonica. A Simulated structure is arranged in the program S2A and a file is generated, which contains all layout information and which can be imported into AUTOCAD. This program is only used to generate plot files, which are directly used by the photo plotter.
This generates the mask on a photographic film using a laser, directly at the final dimensions. The accuracy of the plotter according to the manufacturer is in the order of 0.1 mm. After that the film is developed, one of the metallic layers of the substrate is covered with a thin

[4] R04003TM is a trademark of Roger Co. It is distributed in Europe by Rogers-Mektron, B - 9000 Genr, Belgium.

photosensitive film, and the other layer covered with a protecting plastic film by spraying. The first layer is then used for the microstrip circuits, the second layer will be the groundplane. The substrate is then laid into an oven for fifteen minutes at 70 degrees Celsius. The sensitised substrate is then placed into an ultraviolet exposure machine, with the mask pressed against the photosensitive layer. The UV reproduces the pattern of the mask on this layer, which must be thin in order to achieve an accurate reproduction. The exposed substrate is developed in a chemical product, which removes the photosensitive layer where it was exposed to the UV radiation. The developed substrate is then etched in a chemical product to remove the metal where it is no longer protected by the photosensitive layer. Now the remaining photosensitive layer is removed with acetone and the circuit is rinsed. To protect the conductors against oxidation, a film of conductor protection is sprayed onto the surface.

In this way, all of the test circuits were manufactured up to the 4x4 Butler matrix. Because of a size limitation of 20x30 cm, the 8x8 Butler matrix had to be manufactured by a company.

4.2.2 About Microwave Harmonica

For the design of the microwave components I used Microwave Harmonica version 6 from Compact Software Inc[2]. Microwave Harmonica is a general purpose CAD package for performing microwave and lightwave simulation and optimisation under Windows. It is a popular product for synthesis, analysis, and optimisation of microwave circuits. The prediction of the complete circuit performance is based upon a circuit description using models from an element library. The mathematics are solved using sparse matrix solution, full nodal noise analysis, and powerful modelling algorithms.

A drawback of Microwave Harmonica is that the program takes the length between nodes as given by the user, and does not check if they are physical realisable. This can be solved by a clever connection of the nodes and by thourogly predictions of the lengths. As a last check the physical layout of the circuit structure has to be examined in a CAD-program, such as S2a or Auto-CAD.

Another shortcoming is that the program only takes coupling into calculation if it is modelled with the appropriate element. In other words, for a complex structure consisting of many elements the overall performance is affected by the coupling between many elements, and this is not calculated by Microwave Harmonica. The designer can to a degree work around this problem by keeping enough space between two parallel lines to make the coupling negligible.

4.3 Correction of Relative Permittivity

An accurate knowledge of the substrate permittivity is of prime importance when realising printed microwave structures. For most microwave substrates, the manufacturers specify the permittivity within relatively tight tolerances. If the permittivity is not known accurately, important errors can occur in the microwave structures which would degrade the performance. Fluctuations in the actual permittivity value can occur due to manufacturing tolerances or because the substrate gets moist.

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[2] Compact Software Inc. 483 McLean Blvd & Corner of 18th Avenue, Pateson, NJ 07504 USA, TEL: 201 881-1200, FAX: 201 881-8361

After that the first prototypes were measured and the performance deviated much from the predicted values, the thought was raised that the relative permittivity ε_r of the substrate was not equal to 3.36 to 3.40, which the manufacturer had specified.

To measure the permittivity of a substrate the designer can choose among several methods (See [A3]). The method I used relies on the measurements of the resonance frequency of a half wavelength long resonator which is coupled to the transmission lines via gaps. Its configuration is shown in Figure 4.1.

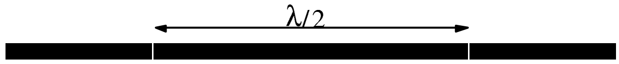

Figure 4.1 Line resonator

The method follows this approach: Starting from the known relative permittivity ε_{appr} the length of the resonator is chosen to be half of the wavelength at the frequency of interest (2.45 Ghz). A mask is realised for the resonator and its coupling lines, the substrate is etched, and the resonances of the structure are measured with a Network Analyser. After that the exact dimensions have to be measured to get the real dimensions of the structure as accurately as possible. Then, from the measured data of the resonant frequency and the real dimensions, the relative permittivity ε_r is changed in the Microwave Harmonica simulation so the same resonant frequency is achieved. This relative permittivity ε_r achieved in the computer simulations correspond to the actual one, and the relative permittivity has been determined.

The method provides some advantages. The test circuit is closely related to the actual structure and uses an actual microstrip circuit to measure a microstrip substrate.
But it has also a few drawbacks. The line resonator is due to its small size vulnerable to local variations of permittivity. Further on, its implementation could give variations of the shape, e. g. tooth-edge, which could not be accounted for in the computer simulation.

I made two identical line resonators in the implementation to minimise the error caused by fluctuations of the parameters and to be able to study the error caused by the variations of these parameters. The resonators achieved a resonance frequency of 2.375 GHz and 2.370 GHz. Hence, a negligible variation (0.3 %).
These resonance frequencies correspond to a relative permittivity of 3.62. This value is far away from the 3.38 the manufacture specified.

In order to check the correctness of the simulation,. I let also another simulation program solve the same problem. Also this time the result was the same. The reasons for the variation of the relative permittivity are hard to tell, but it is not unusual that a substrate has, or gets, another relative permittivity than specified. In this case it could have been so that the substrate was moist, or that the Network Analyser had a malfunction. To test this, the substrate was laid to dry in a temperature of 70 degrees for 18 hours. The resonance frequency was still the same. The higher resonance frequencies up to 10 GHz were measured by another Network Analyser. The result gave the same relative permittivity as before.

Conclusions: The computer program and the Network Analyser work well, and hence, **the relative permittivity has to be ε_r = 3.62 for the actual substrate**.

4.4 Implementation of 90º Hybrids

4.4.1 Theory

The 90°-Hybrid is a well-known circuit in microstrip technique. It consists of a main line which is coupled to a secondary line by two quarter-wavelength long sections spaced one quarter wavelength apart, thus creating a square approximately one wavelength in circumference. This could also be done by means of a circle with the same length, a so called ring-hybrid or rat-race. The coupling factor is determined by the ratio of the impedance of the shunt and series arms according to Figure 4.2

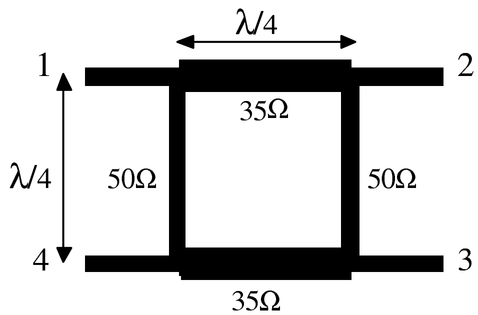

Figure 4.2: The principal structure of a 90°-Hybrid

When a signal is introduced at a port (1) the signals at the two output arms (2, 3) are equal in amplitude but have a 90 degrees phase difference between each other. This 90 degrees relationship is perfect only at one frequency and varies as frequency varies. Ideally, no signal should appear at the fourth port (4). The same thing happens of course if a signal enters one of the other ports.

4.4.2 Normal 90° Hybrid

Different concept of 90 degrees Hybrids were investigated and the structure shown above was decided as the best for the Butler matrix.

I implemented two different configurations of the normal hybrid. First of all, I had to develop and measure the ordinary one above. However, for a compact design of the Butler matrix the connections pointing were into the wrong directions, and a I had to develop a new structure that had the arms 90 degrees rotated compared to the first one. The two circuits attained equal performance.

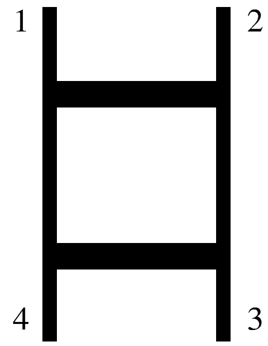

Figure 4.2: 90 degrees hybrid with the arms 90 degrees rotated compared to the normal design.

Measured value of the normal 90 degrees hybrid are shown in Table 4.2. Because the elements should work within the whole ISM-band, the poorest measured value in the ISM-band are shown for each parameter. This values are likely to be at the lower or higher frequency of the ISM-band.

property	value	freq. [GHz]
mean. split	3.22 dB	-
unbalance	<0.25 dB	2.48
isolation	>23 dB	2.40
return loss	<-21 dB	2.40
phase error	<2°	2.48

Table 4.2: Measured value of the normal 90 degrees hybrid. Note that these are the poorest obtained in the whole ISM-band.

One of the parameters of interest for the normal 90 degrees hybrid is the *mean split* of the signal entering the structure. Ideally this one should be 3.0 dB, but losses due to substrate and reflections decrease it to 3.2 dB. There is some *unbalance* between the transmitted signals (<0.25 dB) but with a quite small *phase error* of two degrees. An *isolation* higher than 23 dB and a *return loss* lower than -21 dB are achieved within the whole ISM-band at 2.45 GHz.

4.4.3 Broadband 90° Hybrid

The fundamental limitation of the normal 90° degrees hybrid is, of course, its bandwidth, which is narrow. This restriction can be overcome by adding additional sections which is a technique for broadbanding. The shunt arms should ideally have impedances of 120 ohms which is the upper limit for a practical construction because it will give a width of the strips of about 0.2 mm and this is the thinnest line that can be manufactured at TU-Wien.

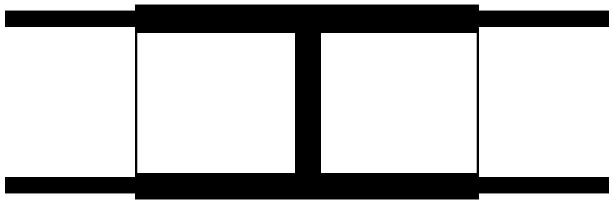

Figure 4.3: Broadband crossover

I developed, implemented and measured this structure and the data can be seen in Table 4.3. The dimensions were verified with a microscope and it could be verified that there were no problems to manufacture a stripwidth of 0.2 mm

I tried also to implement a structure with the connecting arms in other directions, but this was impossible to manufacture because the ideal width of some strips were too narrow.

property	value	freq. [GHz]
mean. split	3.25 dB	-
unbalance	<0.15 dB	2.48
isolation	>30 dB	2.48
return loss	<-30 dB	2.48
phase error	<0.6°	2.48

Table 4.3: Measured value of the broadband 90° hybrid. Observe that these are the poorest obtained in the whole ISM-band.

According to table 4.3 gives the broadband structure a better performance within the whole ISM-band than the normal structure. Note here that the phase error between the two arms only are 0.6 degrees but the mean split is higher. The reason for a higher mean split are to find in that the circuit is bigger, which gives that the signal suffers more from losses due to the substrate.

4.5 Implementation of Crossovers

4.5.1 Theory

In the Butler matrix the signal paths have to physically cross over while maintaining high isolation.

This could be made by letting one of the microstrips go over the other one, like a bridge, by adding a substrate between them. But this gives extensive work during the manufacturing and the signals is perhaps nevertheless coupled or affected by the discontinuities.

Another possibility could be to use a multilayer substrate with a groundplane in the middle and the circuit elements on both sides. The major disadvantage here is that I cannot manufacture such elements without professional help, and that the vias are complex to be modelled in the simulations.

I found the third solution in [M8] which allows a 2-dimensional crossover of the two signal. This is rather good from my point of view, because it enables me to design the whole Butler matrix in one complete circuit without any discontinuities. The complete circuit will probably be rather big compared to a multilayer structure, but this is not a serious shortcoming as long as it is in the same size as the antenna.

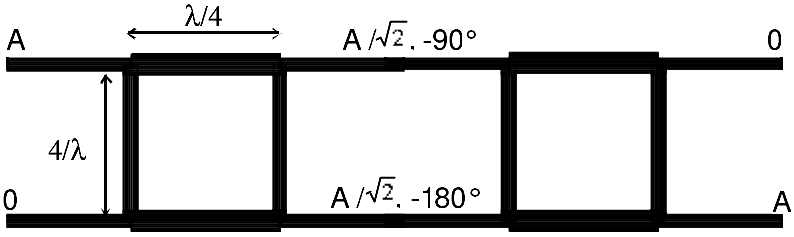

Figure 4.4: Crossover by two connected 90° hybrids

The way the crossover works is at the same time clever and trivial. If two 90 degrees hybrids are cascaded as in Figure 4.4, it can be shown by applying standard hybrid analysis techniques that the signal emerges only at the diagonal port with, theoretically, no insertion loss. Very little power emerges from the remaining two ports and consequently, high isolation between two crossing signals can be achieved.

4.5.2 Normal Crossover

I started by connecting two 90 degrees hybrids and thereby saw that it was possible to achieve a crossover. Further studies showed that the two parallel arms with 50 Ohm in the middle of the structure could be replaced by a single 25 Ohm and I went on and implemented this structure. The measured values are listed in Table 4.4.

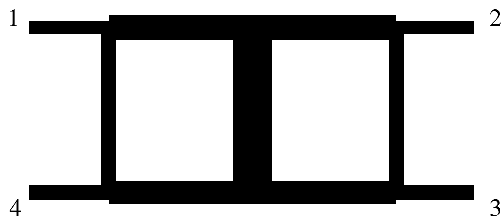

Figure 4.5: Normal crossover

One of the parameters according to Table 4.4 is the *coupling,* which is how much of the signal that is transmitted through the structure. The isolation lettered according to between which ports it is measured. here we see that an isolation of only 17 dB is achieved between ports 1 and 4.

property	value	freq. [GHz]
coupling	> 0.35 dB	2.40
$isolation_{14}$	>17 dB	2.40
$isolation_{12}$	>30 dB	2.40
return loss	<-20 dB	2.40

Table 4.4: Measured data for the normal crossover.

4.5.3 Broadband Crossover

The next step was to connect two broadband 90°Hybrids. I did this and measured the final structure and achieved outstanding performance over the whole ISM-band, as can be seen from Table 4.5.

A note about the size of a structure has to be done. While broadband structures have the advantage of good performance over a wider spectrum, they have the disadvantage of requiring a greater amount of circuit area, increased line lengths which result in additional insertion losses.

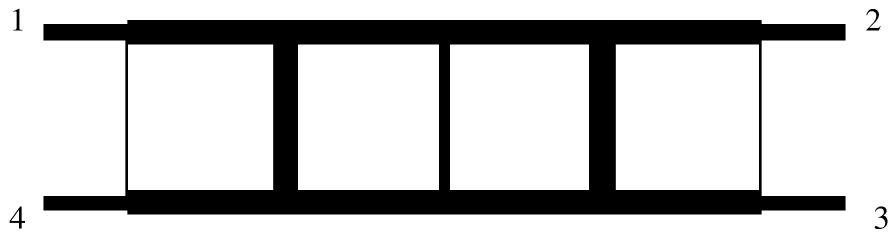

Figure 4.6: Broadband crossover

property	value [dB]	freq. [GHz]
coupling	>0.30	2.40
$isolation_{12}$	>40	2.40
$isolation_{14}$	>50	2.48
return loss	<-30	2.48

Table 4.5: Measured data for the broadband crossover

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4.6 Study of Phaseshifters

The Butler matrix require phaseshifters with three different values; 22.5° ,45° and 67.5°.

4.6.1 Normal Phaseshifter

The normal phaseshifter is quite simple. Every line that is longer than a reference line by a certain amount introduces a phase shift. For instance, the actual length to obtain a 45° phase shift is

$$\lambda_{sub} / 360° \cdot 45° = 9 \text{ mm} \tag{4.1}$$

where λ_{sub} is the wavelength on the substrate defined as

$$\lambda_{sub} = \frac{c}{f} \frac{1}{\sqrt{\varepsilon_{ff}}} \tag{4.2}$$

The phase error for this kind of phaseshifters can be expressed as

$$\varphi_{err} = \frac{\Delta f}{f_0} \frac{\Delta l}{\lambda_o} 360° \tag{4.3}$$

where f_0 is the frequency and λ_o the wavelength on the substrate at resonant frequency, Δf is the difference in frequency and Δl is the difference in length between the lines.

4.6.2 Broadband Phaseshifter

A broadband phaseshifter is possible to achieve in microstrip by two coupled transmission-lines, as shown by Schiffman [M4]. In comparison with a reference microstrip, which has the same phase at 2.45 GHz, the phase response from the coupled lines will be more independent of the frequency. Thus, the reference line can be made longer until the two lines get the same phase response and a differential phase gap occurs.

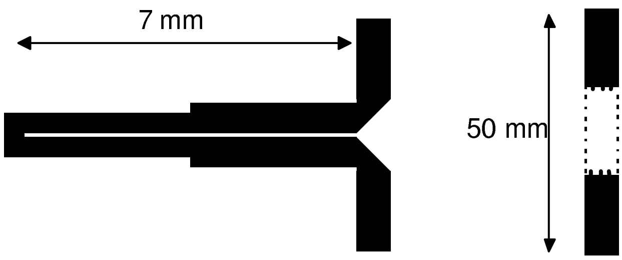

Figure 4.7: Principal structure of a stepped broadband 67.5°-phaseshifter with coupled lines and reference line.

In my design of the phaseshifter I soon came to the conclusion that the return loss was unacceptable high, about-10 dB.

I found a publication [M5] which describes an implementation of this phaseshifter. By letting the width of the coupled lines be different, a so called stepped design, the return loss can be lowered to, theoretically, -40 dB in the ISM-band. So far so good.

For my work I choose not to implement these phaseshifters and list only the theoretical performance (Table 4.6). I will come back to the reasons in the next chapter during the selection of the elements of the Butler matrix.

	67.5° phaseshifter	
property	**Line**	**Stepped Broadband**
return loss	-∞	-40 dB
phase error	<1.4°	<1.2°

Table 4.6: Theoretical performance of a 67.5° phaseshifter implemented as a line or a stepped broadband structure.

Chapter 5

Butler Matrix

5.1 Study of Influences

5.1.1 Circuit Isolation

Perhaps one of the most significant problems when integrating many circuit elements on the same substrate is the isolation between the elements. To investigate coupling in a circuit, I modelled different interaction scenarios in Microwave Harmonica.

One of the most interesting questions is, how close to each other can I place two parallel lines without suffering too much from coupling? In the literature, a common rule is two or three line-widths. However, I wanted to investigate this, so I simulated different dimensions of lengths and gaps in Microwave Harmonica with an element that is suited to calculate coupling.

The result was, that for two parallel lines with a width[7] of 1.8 mm and with a length of 10 mm, it is necessary to have a gap of 3 mm to get a coupling lower than 30 dB. On the other hand, if the lines are extended over 50 mm a gap greater than 6 mm is necessary to avoid the same coupling. Hence, it seems that three line widths is a good rule. However, for a line width of 0.2 mm, e. g. the shunt arms in the broadband hybrid and the broadband crossover, this rule can not be applied. The reasons for this is that the electromagnetic field of a thin line is to a great deal in the area around the line. As can be seen in Figure 2.7.

Another interesting question is how big the interaction is, if there is a gap in a line. This was of great importance to know before I could go on and compact the dimensions of the Butler matrix by placing the elements as close as possible. I modelled this with different widths of the lines and with different dimensions of the gap. I came to the conclusion that a gap of 2 mm is allowed to get a isolation higher than 40 dB.

5.1.2 Protection Spray

To avoid that the final Butler matrix would undergo changes due to oxidation, humidity, dust et. al., the microstrip lines must be protected with a plastic-spray. In order to investigate the influence of this spray on the Butler matrix, I first tested it on the line resonators. The spray showed very little influence to the performance of the resonators, both regarding the coupling and the resonant frequency.

[7] The width of a 50 Ohm microstrip line is depending on the substrate. On my substrate the 50 Ohm line has a width of 1.78 mm

In a later stage, I did the same to the measured 4x4 Butler matrix. This check gave also that **the protection spray has very little influence on the performance of the microstrip circuit**.

5.1.3 Cover

The Butler matrix has to be fixed above a metal plate that at the same time acts as a cover from the environment and as a reflector for the antenna. The distance between patches and reflector should be a quarter of the wavelength in space, i.e. 30 mm, thus the same for the Butler matrix.

I investigated the influence of this cover by placing a groundplane at the actual height in an experiment. The performance of the circuit showed **very small or no variations**. As a last check, I did the same for the 4x4 Butler matrix, nevertheless with the same conclusion.

5.2 Performing Simulations

The simulations of the Butler matrix were carried out in MATLAB, as described in chapter 3.

The Butler matrix should stand up to the requirements in the whole ISM-band. Therefore, in the simulations I chose to use the poorest value obtained from each element during the measurements. These values are likely to be at the boundary of the ISM-band. (i.e. 2.40 Ghz or 2.48 Ghz). To the measured value, I added a random error which accounted for the unknown coupling and randomly occurring errors due to the manufacturing.

When implementing the Butler matrix the question of primary interest to investigate is: *Which elements should I implement as normal structures and which should I implement as broadband structures?*

The reader may find the answer trivial, but bear in mind that not all circuits can be mounted on the same substrate as broadband structures, because there is not enough space. The reasons why I did not change the actual substrate to one with larger dimensions are found in the properties of the substrate. I have developed my circuits with respect to the actual relative permettivity of 3.62, which differed much from that in the datasheet of the manufacture. If I changed the substrate I surely would not get a substrate with the same properties, which would force me to tailor new elements with respect to the new relative permittivity. And you do not waste a substrate when it takes two months to become a new one.

In order to answer my main question, I decided to study the influence of each element on the antenna pattern. The simulations were accomplished with every element in the butler matrix treated as ideal, except for the investigated element which had its measured properties.

The next step was to combine the elements with each other to investigate possible interactions. Hence, several combinations had to be investigated before a statement could be achieved. I studied also combinations of normal and broadband structures of the same kind of element but at different locations in the butler matrix. During this simulations a random error was added to the overall performance of the elements in order to simulate unknown influences.

5.3 Result and Conclusions of Simulations

5.3.1 Influence of Elements

The influence form each kind of element on the performance of the Butler matrix were investigated by keeping all elements ideal, except the investigated element, that had the properties obtained during the measurements. The influence of each kind of element to the sidelobes is presented in Table 5.1.

	normal structure	**broadband structure**
everything ideal	-24 dB	-24 dB
phaseshifters	-23 dB	-23 dB
hybrids	-23 dB	-21 dB
crossovers	-17 dB	-21 dB

Table 5.1: Maximal sidelobe of the antenna pattern due to the influence from one kind of element.

Note here that the performance of the broadband phaseshifter is just theoretical. Nevertheless we attain the same performance as with a normal phaseshifter.
It is obvious here that the crossovers have the largest influence on the sidelobes.

5.3.2 Conclusions Obtained During the Simulations

I made some conclusions during the simulations:

- **Different Lengths of Input Lines Necessary**
  To be able to obtain low sidelobes by the superposition of two beams, the beams have to be superpositioned with the right phase. However, to be able to achieve the right phase the input ports of the Butler matrix must be fed with the appropriate phases of the signal. This can easily be implemented in the structure as different lengths of the input lines to the first row of hybrids on the substrate.
  The right phases to obtain a cos-illumination are shown in table 5.2.

port	4L	3L	2L	1L	1R	2R	3R	4R
phase	-180°	-22.5°	157.5°	0°	0°	157.5°	-22.5°	-180°

Table 5.2: Phase of inputs to Butler matrix for optimum superposition of two adjacent beams.

- **The Antenna pattern suffers from sidelobes**
  Of all the parameters of the pattern characteristic that are interesting for a user, e.g. crossover levels and beamwidths, the sidelobes are most affected by errors in the

illumination of the antenna. In the simulations I thus concentrated on the behaviour of these.

5.4 Special Requirements for the Design of the Butler Matrix

Before I present my selection of the elements in the Butler matrix, I would like to state some of the factors I had to deal with before I could make a definite statement.

When I want to implement a circuit in microstrip technology, there are certain basic rules and techniques which can be applied in order to increase the probability of success, most important are the methods of layout. Circuit elements should be laid out so that they do not tend to interact with each other. In the case of parallel lines a big line-spacing should be maintained to minimise coupling, as described in chapter 5.1.1. Similarly, it is desirable to eliminate as many bends as possible. Although mitered bends have minimum reflections, a big number of these bends could introduce so many uncontrolled reflections that the desired overall circuit performance may not be achieved. It is also important to lay out the individual circuit functions in a logical flow, within the available dimensions of the package.

A very limiting condition, which can be imposed on the designer of the microstrip layout, is to pre-determine the locations of the connectors. This means that the circuit layout must conform to the input and output locations. In my implementation the outputs of the Butler matrix are restricted to have a distance of 60.3 mm and the inputs should be kept close together to enable easy connection to a selector. These conditions must be met and it is up to me as the designer to work around the limitations. As a result, logical flow and avoidance of bends cannot be kept in the first line and the performance of the circuit will be lowered in order to meet the necessary conditions

In this work the major goal is to achieve the best antenna pattern with respect to the requirements (see Chap 1.5). The fact that the *antenna pattern should have a satisfactory characteristic in the whole ISM-band* calls for a broadband structure of the Butler matrix. But broadband elements are bigger than normal ones, and if all elements of the Butler matrix were implemented as broadband elements, the system would not be able to cope with the restricted area of the substrate.

Another feature of the Butler matrix is that the same electrical length must be obtained between the hybrids. This condition is also valid for the lines from the input and output ports to the first hybrid. If this is not kept, phase errors will be introduced that ruin the performance of the system.

5.5 List of Special Requirements for the Butler Matrix

- Input ports close together
- Output ports spaced with a distance of 60.3 mm
- Electrical length equal between the Hybrids
- 50 Ohms lines spaced at least 4 mm apart for shorter lines (<10 mm)
- 50 Ohms lines spaced at least 8 mm apart for longer lines
- No lines closer than 10 mm to the border of the substrate
- Avoid bends if possible
- As short line length as possible to avoid losses
- Keep the structure smaller than 30x45 cm

5.6 Selection of Components

Here I will present the elements I selected to implement the Butler matrix with a brief explanation:

5.6.1 Broadband Crossovers

The simulations showed that two signals that cross each other must maintain a good isolation from each other. The broadband crossovers have outstanding performance compared to the normal structure. In the simulations summarised in table 5.2 the normal crossover showed that it was able to create sidelobes as high as -17 dB. Furthermore, the sidelobes will grow even larger when the errors from the other elements are added.

The problem with the broadband crossover is that has a big area. To be able to implement the broadband crossover on the substrate some implementation rules must be neglected. The logic flow must stand back. Thus, some more bends are introduced and some lines have to be extended. Also the space between elements and lines has to be kept relatively small. But, I am absolutely convinced that the structure with the broadband crossover is likely to achieve a considerably better performance than a structure with normal ones. Even if some broadband crossovers were changed against normal ones in order to get more free area, I am of the firm opinion that the overall performance would be degraded.

5.6.2 Normal Hybrid

The broadband hybrid showed to be very difficult to place in the circuit in a good manner. If I would like to choose the broadband hybrids, I could not use the broadband crossovers simultaneously because of the limited area and that would be fatal. However, the normal hybrid has comparable influence to the antenna pattern (Table 5.2) as the broadband one and is much easier to implement in the system due to its smaller size. And it will be even easier, if the connecting arms are rotated by 90 degrees.

5.6.3 Normal Phaseshifters

The simulations (Table 5.2) show clearly that the broadband structure is comparable to a simple extended transmission line even if I use the good theoretical properties for the broadband structure. A real structure will suffer from manufacturing errors and is likely to have poorer features than the theoretical one. The broadband structure would of course be better if the Butler matrix had to work in a larger frequency band. However, I am quite convinced that the normal phaseshifter is sufficient for the ISM-band.

5.7 Result from Simulation of the Whole System

The complete system was simulated with selected components with measured values and added random errors. The result gave me a clue of the performance of the final product and if this would work. The simulation showed **that a maximum sidelobe level of about -21 dB to -17 dB was achievable**. Note that the simulations show different values for each simulations according to the added random errors in the simulations.

The conclusion was that the system could work with this choice of elements

5.8 Implementation of the 4x4 Butler Matrix

As a next step I had to verify if my conclusions were true. By implementing a smaller Butler matrix with the chosen elements I was able to check this.

I implemented a 4x4 Butler matrix, as shown in Figure 5.1 ([B5]).

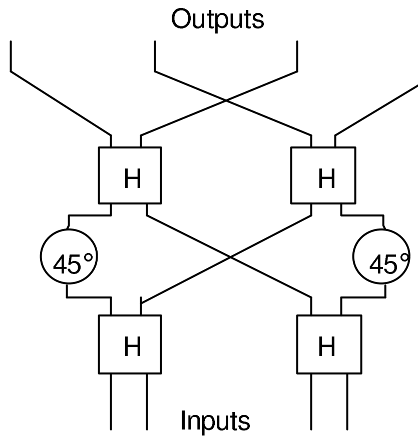

Figure 5.1: Structure of the 4x4 Butler matrix

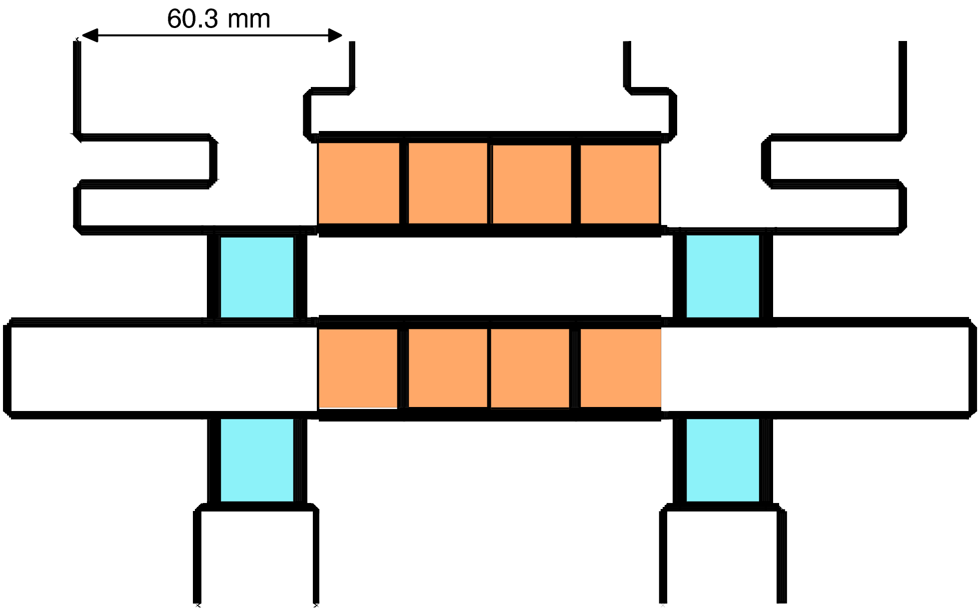

Figure 5.2: Layout of the 4x4 Butler matrix. Marked in the circuit are the four hybrids and the two crossovers.

5.9 Result and Analyse of the 4x4 Butler Matrix

I measured the scattering matrix of the implemented 4x4 Butler matrix with a Network Analyser. From this scattering matrix, I could go on and calculate the antenna pattern which is shown in Figure 5.3.

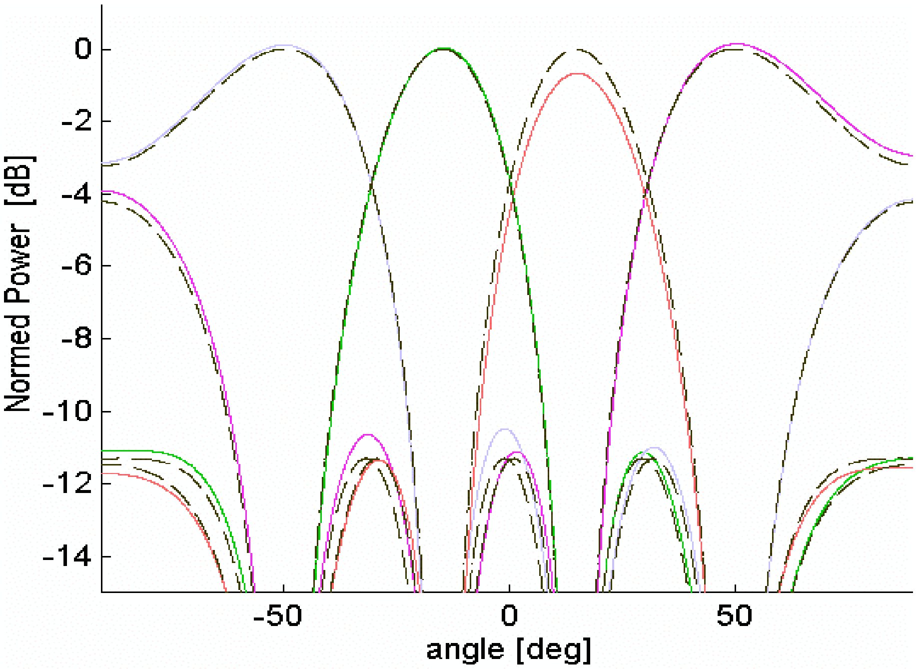

Figure 5.3: Antenna pattern of the 4x4 Butler matrix calculated from the measured S-parameters: solid line, Ideal: dotted line.

The antenna pattern showed to be very good over the whole ISM-band. In short, the 4x4 Butler matrix worked.

To really be able to predict the performance of the 8x8 Butler matrix, I decided to do this:

1. Measure and calculate the antenna pattern from the 4x4 Butler matrix
2. Change the parameters of the elements in a simulation of the 4x4 Butler matrix until
   the same performance of the pattern is achieved.
3. Simulate the 8x8 Butler matrix with these new parameters.
4. The calculated antenna pattern should now be close to the real one.

The calculated antenna pattern showed that the highest sidelobe would not be higher than -18 dB in the whole ISM-band, and I could make some conclusions:

- The 4x4 Butler matrix worked well.
- The elements worked together.
- The simulation method is able to predict the performance of the system.
- It is possible to achieve sidelobes lower than -18 dB for the 8x8 Butler Matrix

It was time to move on.

5.10 Implementation of the 8x8 Butler Matrix

The design of the layout of the Butler matrix was somewhat difficult. The used program is able to calculate the necessary lengths between the elements, but it does not check, if it is physically realisable. So, I had to help the program after every optimisation by calculating the physically value with a pocket calculator. The final structure of the Butler matrix is shown in Figure 5.4.

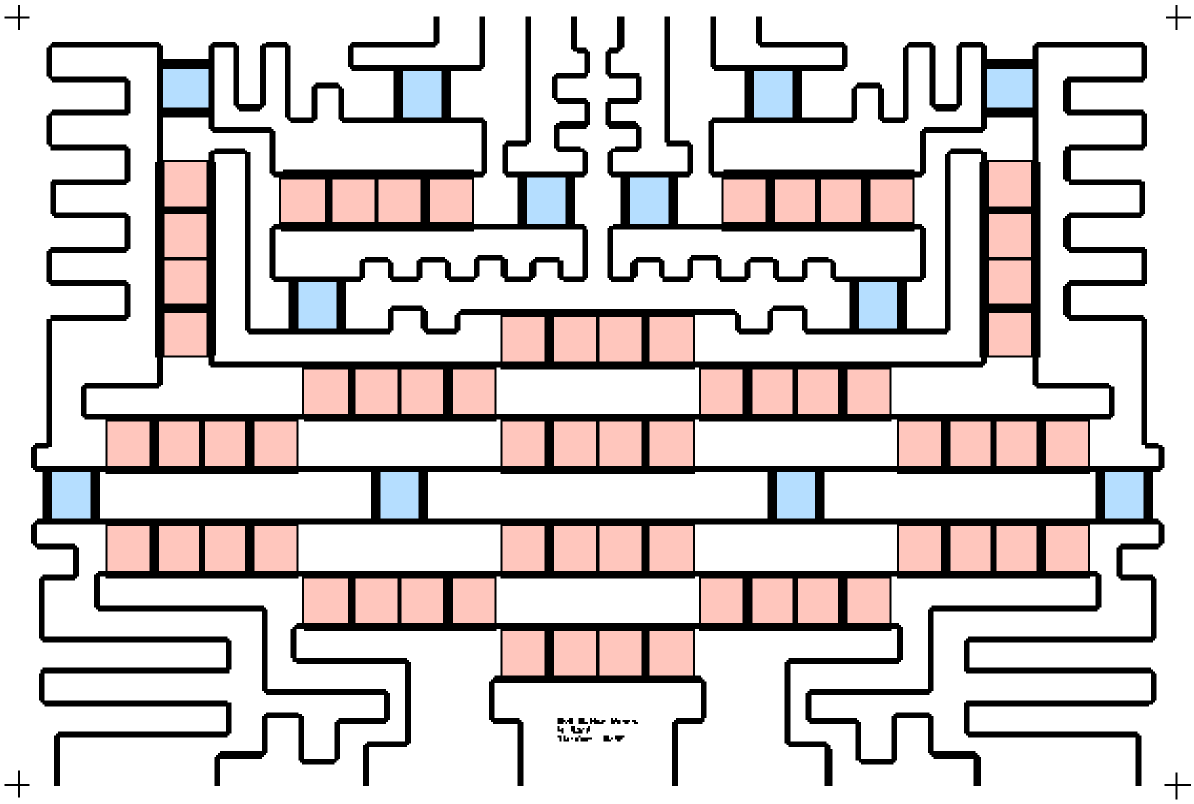

Figure 5.4: Final version of the 8x8 Butler matrix. Marked in the figure are the location of the crossovers and the hybrids. Notice the different lengths of the input lines which are necessary for two beams to be superpositioned in phase.

The final Butler matrix was too big to be manufactured at TU-Wien, so this was made by a company.

5.11 Result of the 8x8 Butler Matrix

I measured the scattering matrix of the 8x8 Butler and calculated the antenna pattern. Notice here that when I mean the antenna pattern I am referring to the array factor. The antenna pattern to be measured is a combination of the array factor and the element factor.

Conclusions:

- Unbalance in output ports <2 dB from mean value
- Phase error in output ports <15° from ideal phase
- It is possible to achieve max. sidelobe < -10 dB for one single beam
- It is possible to achieve max. sidelobe < -18 dB for two superposed beams
- The 8x8 Butler matrix worked

5.12 Losses of the Butler Matrix

A microstrip structure always suffers from losses due to the losses in the substrate. The actual substrate is chosen to get as low loss as possible.

A way of estimating the losses in the 8x8 Butler matrix is by using summing the power transmitted from one port to the others, as according to

$$Losses_1 = 1 - \left[10^{\frac{T_{A1}}{10}} + 10^{\frac{T_{B1}}{10}} + 10^{\frac{T_{C1}}{10}} + K + 10^{\frac{T_{H1}}{10}} \right] \quad (5.1)$$

where the scattering element T_{j1} is the transmission from port *1* to port *j*. The transmission element is given in decibel and defined as shown in figure 5.5.

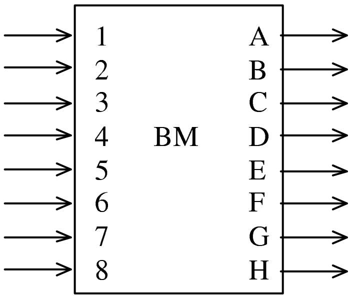

Figure 5.5: Definition of the ports of the Butler matrix

	decibel [dB]	linear	power
T_{A1}	-11.4	0.27	0.07
T_{B1}	-11.6	0.26	0.07
T_{C1}	-11.3	0.27	0.07
T_{D1}	-11.4	0.27	0.07
T_{E1}	-12.0	0.25	0.06
T_{F1}	-11.2	0.28	0.08
T_{G1}	-11.8	0.26	0.07
T_{H1}	-11.8	0.26	0.07

Table 5.3: Measured values of the transmission coefficient at 2.40 GHz

If equation 5.1 is used with the values from table 5.3 is the losses

$$Losses_1 = 0.44$$

Hence, 40 percent of the power put into the 8x8 Butler matrix do not reach the antenna. This gives that the Butler matrix do not suffers to much from losses.

Chapter 6

Antenna Array

The implementation of the array was based on an earlier antenna developed by Kuchar [A2] at TU-Wien. Here I will give only a brief description of the structure, the manufacturing and the measurements of the antenna.

6.1 Array Design

The design of the antenna is quite identical to the one made by Kuchar, except in one detail. I use an array of ten elements and not one with nine elements.The reasons for building the antenna with ten elements and not eight, is that the two elements at the end of the linear array do not have the same features as the rest. This can be understood by the fact that the two most outward elements have only one nearest neighbour, while all other elements have two nearest neighbours, and therefore influences of mutual coupling are different. One way to get around this problem is to extend the antenna with two more patches which are not excited. This will give each element more equal properties, but on the other hand, also give a longer antenna (120 mm), but it is worth the price.

The antenna is based on the Strip - Slot - Foam - Inverted Patch (SSFIP) structure which was introduced by J. F. Zürcher in 1988 [A1]. The concept is a technique to obtain broadband microstrip patch antennas with significant advantages over standard microstrip antennas in terms of bandwidth, efficiency, weight and cost.

In the SSFIP structure the antenna is built on a thick substrate of low-permittivity material in order to avoid concentrations of the field within the substrate. Ideally, the optimum dielectric substrate should be air, but since the structure then would need a mechanical support to hold the patches, hard foam is used - actually *Rohacell* [A4]. Foam, mostly made of air, exhibit good structural , thermal and electric properties. The relative permittivity for Rohacell is quite near the one for air, $\varepsilon_r = 1.09$ .Foams are quite rigid by themselves and then they are assembled in a „sandwich“ form, the result is an extremely lightweight and resistant structure. Further on, surface waves are not significantly excited on foam substrates, so coupling between elements is very small.

Foam has some drawbacks. First of all, foam does not present a flat, well-defined surface, so metal patches cannot be deposited directly on it. Secondly, foam materials tend to be badly affected by moisture, so, something has to be done to keep moisture out and to protect against other environmental effects. These problems are solved using the *inverted patch* technique. This means, by adding a thin plastic layer on which the metal patches are deposited, and you mount the plastic layer in such way that the printed patch is directly positioned on top of the foam, you get both protection from the environment and a material to mount the patches on. The plastic layer is so thin, so its effect on the radiation characteristics of the antenna are practically negligible.

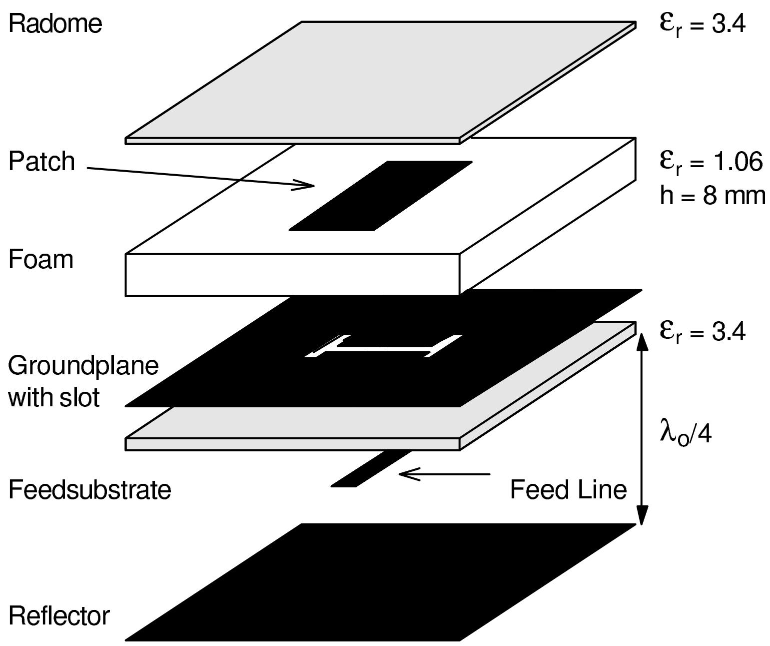

Figure 6.1: Structure of a Strip-Slot-Foam-Inverted Patch (SITE) antenna with an added reflector.

There are a lot of ways to feed a microstrip patch. One of the main problems that occur, is that the feeding line itself act as a radiator. This is solved by placing the groundplane between the feed line and the patch, and let the patch be coupled by a slot in the groundplane. In this way the two functions of radiation and of guided transmission are completely separated from each other. The slot itself should not resonate over the operating frequency band of the antenna because this would produce radiation toward the back of the antenna. The shape of the coupling slot in this case is the H-shaped slot. Why this particular slot form is chosen, and not a simple rectangular slot, depends on the fact that a rectangular one,slot would have to be so long, that it would interact too much with its neighbours. Hence, the length of this slot is shortened by the use of a H-shaped slot, but at the price of higher cross-coupling.

The radiation from the feed line toward the back is avoided by putting a reflector behind the antenna.

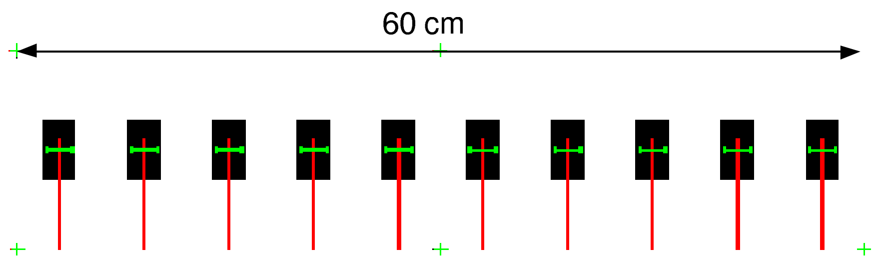

Figure 6.2: The whole array

6.2 Manufacturing

The actual dimensions of the antenna were identical to the ones given by Kuchar [A2]. I drew layers for patches, slots and feed lines, on three different layers in Auto-CAD. The manufacturing of these was done by the same company as for the Butler matrix. To stick to the foam substrate I used a double sided adhesive tape with defined thickness. I waited to mount the reflector until the antenna and the Butler matrix were connected.

6.3 Measurement Results

A way of checking if the antenna is properly matched is to measure the return loss for the inputs to the antenna. As I mentioned in Chapter 1 the bandwidth is defined as the frequency range within the VSWR ≤ 2, which correspond to a return loss of -9.5 dB.

I measured a couple of the ports where the two most interesting are to be found in Figure 6.3., namely the patch in the middle and the patch second closest to the end (The two at the end are not used). The figure clearly shows that the antenna is matched through the whole ISM-band

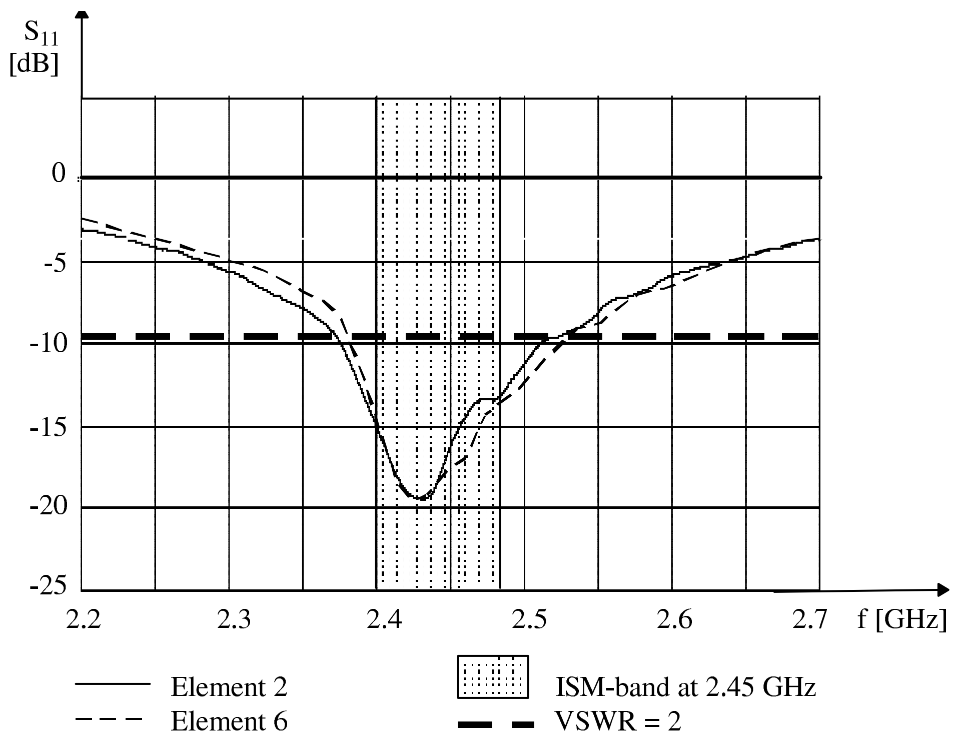

Figure 6.3: Measured return loss for the antenna

Chapter 7

Complete system

7.1 Assembling

The antenna and the Butler matrix were mounted as shown in Figure 7.1. The antenna has to be placed at least 1 m from the ground to get a free view for the radiation. It is also desirable that it can stand without help. Therefore, the antenna and Butler matrix were mounted on a Plexiglas support made at INTHF.

To avoid mismatches the antenna and the Butler matrix were connected directly to each other, as shown in figure 7.1.

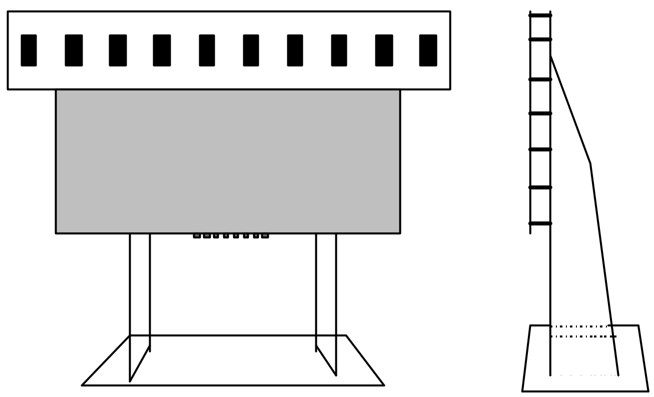

Figure 7.1: The Antenna shown from the front and from the side with the Butler matrix underneath. The circuit of the Butler matrix is between the groundplane and the reflector.

To improve the front to back ratio of the antenna an aluminium reflector was mounted 30 mm behind the patches using 30 mm plastic pins. These plastic pins have a width of approximately 8 mm and make it possible to screw two plates together steadily enough. A second reason for mounting a reflector behind the patches was to protect the Butler matrix from the environment.

After mounting the reflector, I connected the feeding lines of the antenna to the Butler matrix. To be able to connect the these microstrip lines with each other, I lay a thin layer of copper (with the width of the microstrip) above them and secured them together. The next step was to lay the antenna connected with the Butler matrix over the plexiglas. Through the holes drilled in the plexiglas I could make marks on the Butler matrix and the antenna. Hence, the next step was to drill the marks to get holes with exact location.

The two unused antenna elements at the sides of the antenna, which should act as ”dummies”, have to be terminated for a proper function.

7.2 Performing the Measurements

The array antenna pattern fed by the Butler matrix was measured in an anechoic chamber in Forschungs Zentrum Seibersdorf. The chamber in Seibersdorf enabled me to measure at a distance R of 3.00 m between the two antennas. To know if this distance is to close, we have to know where the far-field starts. The far-field for the used antenna was stated in Equation 2.4 and gave R = 3.84 m. When I use a distance of 3.00 m, the approximation should not be valid, but as mentioned in Chapter 2., the higher the distance R is, the higher the level of fine-structure in the pattern can be observed. In this case a sidelobe of -20 dB is not considered too low for a satisfactory measurement.

During the measurements a horn acted as the transmit antenna and the Butler matrix and the antenna as the receive antenna. The measurements were performed with a distance of 3.00 m from the front of the horn to the front of the patches (see figure 7.2.). The antenna pattern was measured for the co-polarisition E-component and accomplished by a sweep from 0 to 360 degrees.

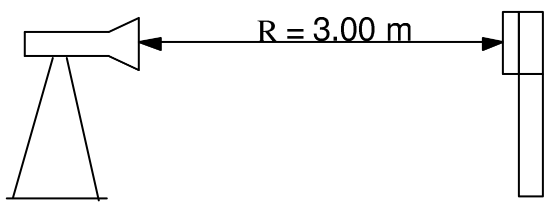

Figure 7.2: The horn (left) and the patch antenna (right)

The measurements were performed with both one single beam and with a superposition of two adjacent beams. Hence, requiring the signal to be fed to two input ports simultaneously. When a single input port was used, the feed net to the Butler matrix was only consisting of a single cable. When two ports should be fed simultaneously, the feed net shown in figure 7.3 had to be used.

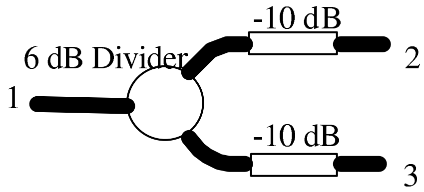

Figure 7.3: Feed net which allows two inputs of the Butler matrix to be fed at the same time.

The feed net comprises two elements to avoid a signal flow in an unwanted direction. However, they also gave a loss of 10 dB of transmitted power. Since there was no 3 dB divider available I had to accomplish the signal split with a 6 dB divider. Note that this has no influence on the shape of the antenna pattern, but the recieved power is decreased due to power losses in the feed net. The split of the signal into the two cables introduce errors due to different lengths of the cables. To investigate the error of the feed net, I measured it with a network analyser. The data is presented in table 7.1.

	2.40 GHz	**2.45 GHz**	**2.50 GHz**
S_{12}	-16.0 dB	-16.3 dB	-16.4 dB
ΔS_{12}	0 dB	0.1 dB	0 dB
$\Delta\varphi_{12}$	3.5°	4°	4.5°

Table 7.1: Measured performance and errors of the feed net

The cables introduce a relative phase error but according to thorough simulations of the Butler matrix, a phase error less than 5 degrees has a very little influence on the properties of the antenna pattern. The amplitude error between the feeding lines is negligible.

The special interest parameter, showing the gain of the antenna, is compared to an isotropic radiator. This enables valid properties of the system when the rest of system should be integrated as a part of the testbed. To be able to study the gain of an antenna pattern from two superpositioned beams, the measured antenna pattern has to be compensated for the loss in the feed net. Hence, a value of 13 dB has to be added to the measured data to achieve the real value which would be achieved by a lossless feed net.

The input port was denoted (Figure 7.4) corresponding to the achieved beam direction counted from broadside.

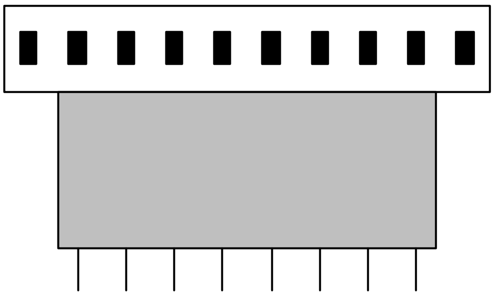

Figure 7.4: The antenna seen from frontside with the input ports corresponding to beams.

The same condition has to be fulfilled for the pattern measurements as for the S-parameter measurements accomplished by the Network Analyser: all unused antenna elements in a measurement cycle have to be terminated with 50 Ohm .

7.3 Measurement Results

This section presents comments on the measured antenna patterns. All measured antenna patterns can be found in Appendix A.

I want to point out, that the measured antenna patterns also comprise the *element factor*. According to the source [A2] the element factor of the actual patch element is quite equal over the angles 310 degrees to 50 degrees from the broadside and at an angle of 60 degrees the element factor goes down below the -3 dB level and declines fast at larger angles. This implies that the measured antenna pattern is decreasing with the element factor of different angles. Since the element factor is zero at a 90 degree angle, it is impossible to achieve a radiation at this angle.

7.3.1 Antenna Pattern from one Single Beam

The eight antenna patterns achieved from a single signal introduced to the Butler matrix at the frequency of 2.45 GHz, which is in the middle of the ISM-band, are shown in Figure A.1-A.8 in Appendix A. In Figure A.9 the measured antenna pattern from port 1L is given for three different frequencies in the ISM-band. All Beams are simultaneously plotted in Figure A.10. In this chapter I only want to show the diagram for beam L1 as an example (Figure. 7.5).

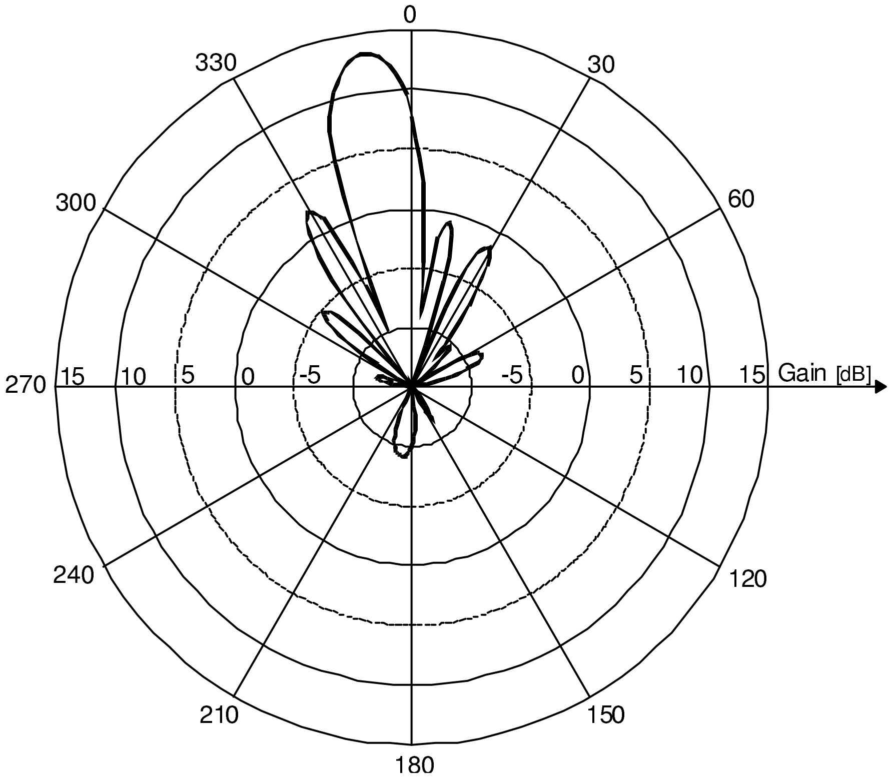

Figure 7.5: Beam direction 1L at frequency 2.45 GHz

The Characteristic of the antenna patterns are best visualised from the simultaneous plot in Figure A.10. Here it is obvious that the antenna gain is decreased for beams close to the endfire direction as the element factor now drops off. The maximum gain for the antenna is measured to be 13 dB over the isotropic radiator, which is a good result. This implies that the losses in the Butler matrix are not too big to enable a satisfactory efficiency of the antenna pattern.

The measured crossover levels are between 3 and 5 below the peak level of the main beam, which is close to the theoretic value of 4 dB for the crossover level for the beams.

In Figure A.10 it is shown that the highest sidelobe has a gain of about 3 dB and the lowest main beam has a gain of 11.5 dB. Unfortunately, this is achieved for the beam 4R giving a sidelobe level of 8.5 dB, as can be seen from Figure A.8. A higher sidelobe level would be achieved if the element factor had not decreased the main beam with about 2 dB in this direction. Hence, **the reason for the slightly different performance for the beams close to endfire is to find in the characteristic of the element factor**. So, the best properties of the antenna patterns are found for the six beams closest to broadside. For these beams the sidelobes are always more than 10 dB below the main beam at a frequency of 2.45 GHz.

To investigate how the characteristic of the antenna patterns are affected by the change of the frequency in the ISM-band, two figures are available. In Figure A.9 the antenna patterns for the beam 1L are simultaneously plotted for the frequencies 2.40, 2.45 and 2.50 GHz. Here we see that there are small differences between the antenna patterns within the ISM-band. The most affected parameters is the gain of the main beam. In Figure 7.6 the gain intothe direction of the main beam is continuously measured from frequency 2.1 GHz to 2.8 GHz. Here it is obvious that the highest gain is between 2.40 GHz and 2.48 GHz, thus in the ISM-band.

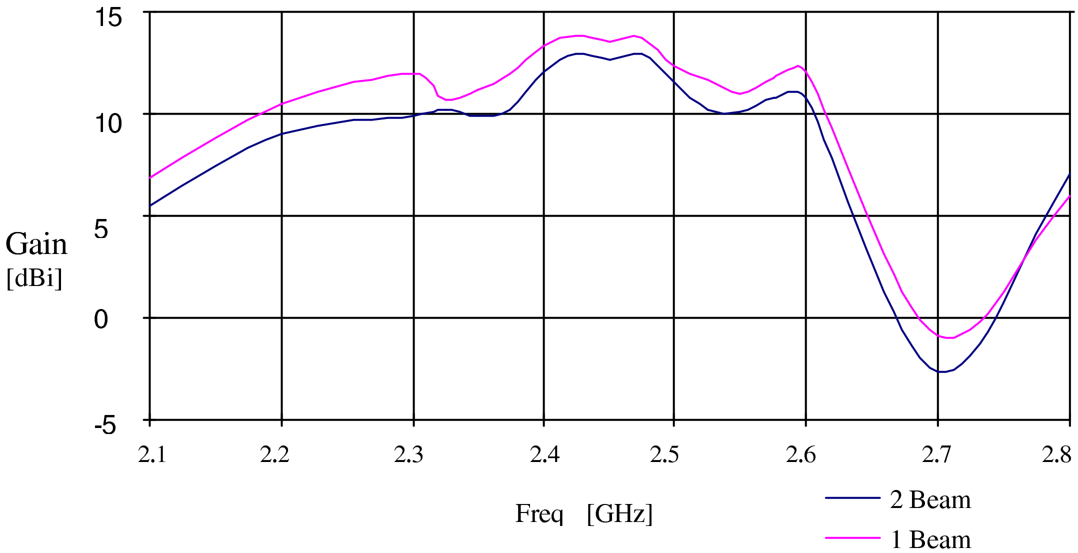

Figure 7.6: Gain for the main beam 1L and the superposition of the beams 1L and 1R as a function of the frequency.

As seen from Figure A.9, the sidelobes are also affected by frequency. But there are slight differences in the levels and the shape of the sidelobes. This is also verified by the measurements of the S-parameters of the Butler matrix. Hence, the antenna pattern obtained at 2.45 GHz does not differ much from the antenna pattern at 2.40 GHz and 2.48 GHz, which makes it possible to predict the properties of the antenna patterns at these frequencies. The conclusion is, that **the requirements of the antenna patterns for a single beam are achieved within the whole ISM-band**.

7.3.2 Antenna Pattern from superposition of two Beams

The seven antenna patterns achieved from a superposition of signals introduced to the Butler matrix at the frequency of 2.45 GHz, which is in the middle of the ISM-band, are shown in Figure A.11 - A.17 in Appendix A. Here beam 1L superpostioned with 1R is shown as an example in Figure 7.7. In Figure A.18 the measured antenna pattern for the superposition of the beams 1L and 1R is given for three different frequencies in the ISM-band. The Beams are simultaneously plotted in Figure A.19.

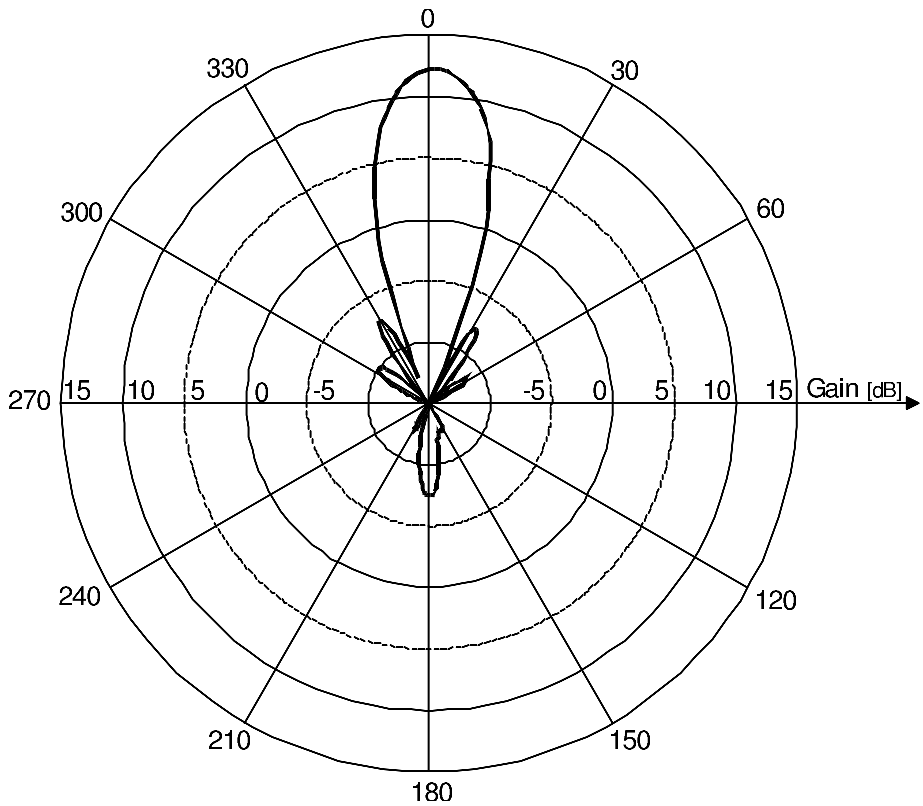

Figure 7.7: The result of superposition of beam L1 and R1 at 2.45 GHz

The characteristics of the antenna patterns are best visualised from the simultaneous plot in Figure A.18. The maximum gain for two superpositioned adjacent beams are, compared to an isotropic radiator, somewhat lower (1 dB) than for a single beam. The reason for that is to find in the superposition of two beams. Hence, the two beams are superpositioned at a point, where the gain is somewhat lower than for the main beam direction.

The crossover levels are generally 2 dB below the peak level of the beam, which is equal to the theoretic value of the crossover level for the beams. The crossover levels are about 10 dBi , which enables the whole view from 305 to 55 degrees to be covered with at least this gain.

The highest gain of the sidelobes is -5 dBi, which gives a minimum difference between the sidelobe and the main beam of 17 dB. Note, that this is the lowest difference achieved for all beams at 2.45 GHz, which is a very satisfactory result. In the ISM-band should the performance not differ too much from this value, as earlier discussed in chapter 7.3.1.

7.3.3 Summary of Measurements Result

Beam	Max. Gain [dBi]	Sidelobe level [dBi]	min crossover level [dBi]
4L	11.3	3.6	9.1R
3L	13.4	0	9.2
2L	13.1	1.4	9.4
1L	13.5	1.2	9.6
1R	13.5	2.3	9.8
2R	13.1	-0.3	9.3
3R	13.4	-1.4	9.2
4R	11.1	3.1	
4L+3L	9.2	-8.2	7.4
3L+2L	9.3	-13.5	7.1
2L+1L	10.1	-10.9	7.7
1L+1R	9.6	-10.1	7.6
1R+2R	10	-9.1	7.2
2R+3R	9.2	-12.7	7.4
3R+4R	9.1	-9.2	

Table 7.2: Summary of measurements result

Chapter 8

Conclusions

This diploma thesis has shown that it is possible to implement an 8x8 Butler matrix in microstrip technique in a completely planar structure without suffering from power losses and poor characteristics of the antenna pattern in the ISM-band. The implemented circuit has a low losses, even though the area of the circuit is rather big and the transmission lines are long. It has also been shown that the coupling on the board could be kept low if the distance between circuit elements were chosen big enough.

Hence, it is possible to implement crosses of two signals with high isolation and high transmission by connecting two broadband 90 degrees hybrids. It was also shown that there was no need for broadband phaseshifters in the structure, and that an implementation with these would probably decrease the overall performance.

The very good prediction of the antenna pattern is to be found in thorough simulations of the structure. Hence, an algorithm that does not consider the reflection losses can also give a good answer if the reflections and coupling between elements are modelled with an added error to the performance of each element. The structure of the implementation of the 8x8 Butler matrix is another reason for a good product. Hence, the idea to modify the simulation model showed to be very good .

A basic requirement for a good function of the circuit is to avoid coupling between elements and transmission lines. This implies that the logical flow of the design process has to be very good. The structure used in this implementation is probably the reason for low coupling, but nevertheless it is small enough to be implemented on the actual circuit.

A good connection of two systems, as the Butler matrix and the patch antenna in this case, is sometimes hard to achieve. The solution to connect them directly to each other showed also to give good performance.

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Appendix A

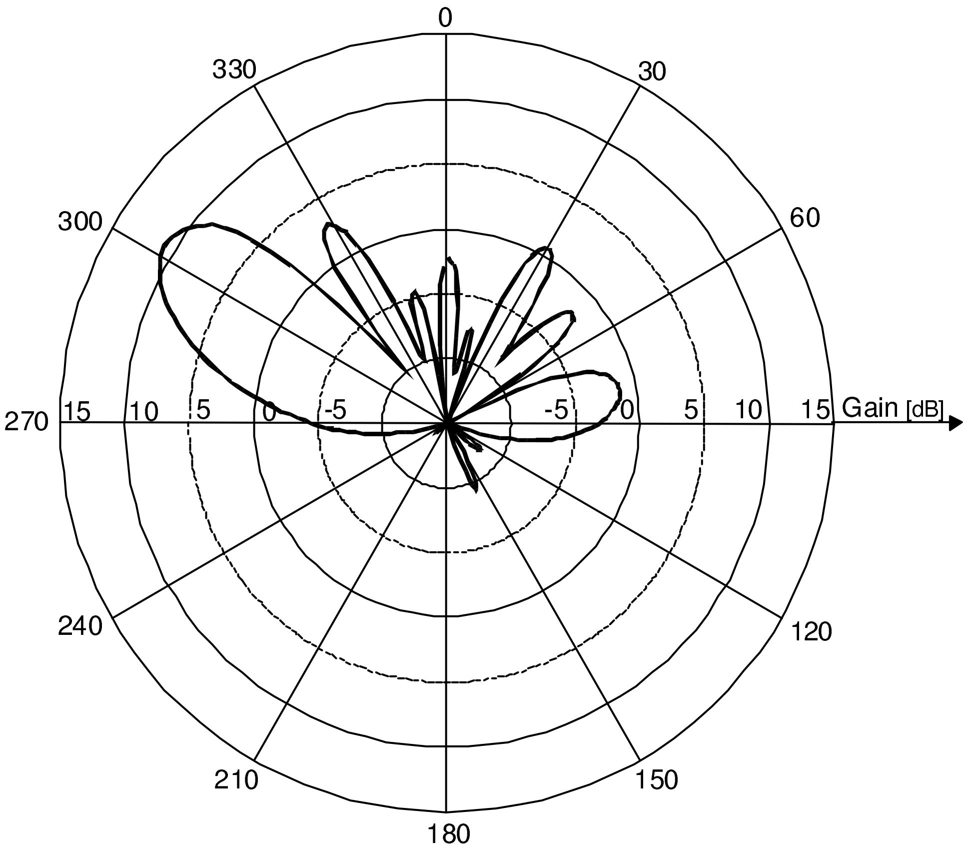


Figure A.1: 4L f = 2.45 GHz

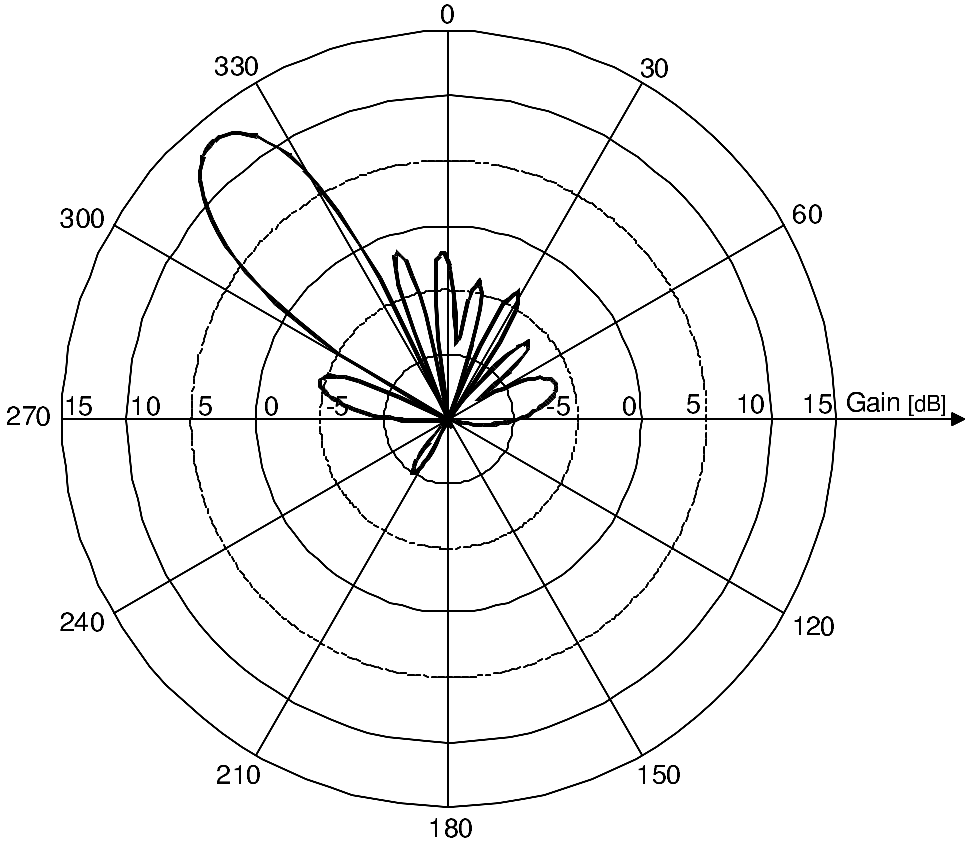


Figure A.2: L3 f = 2.45 GHz

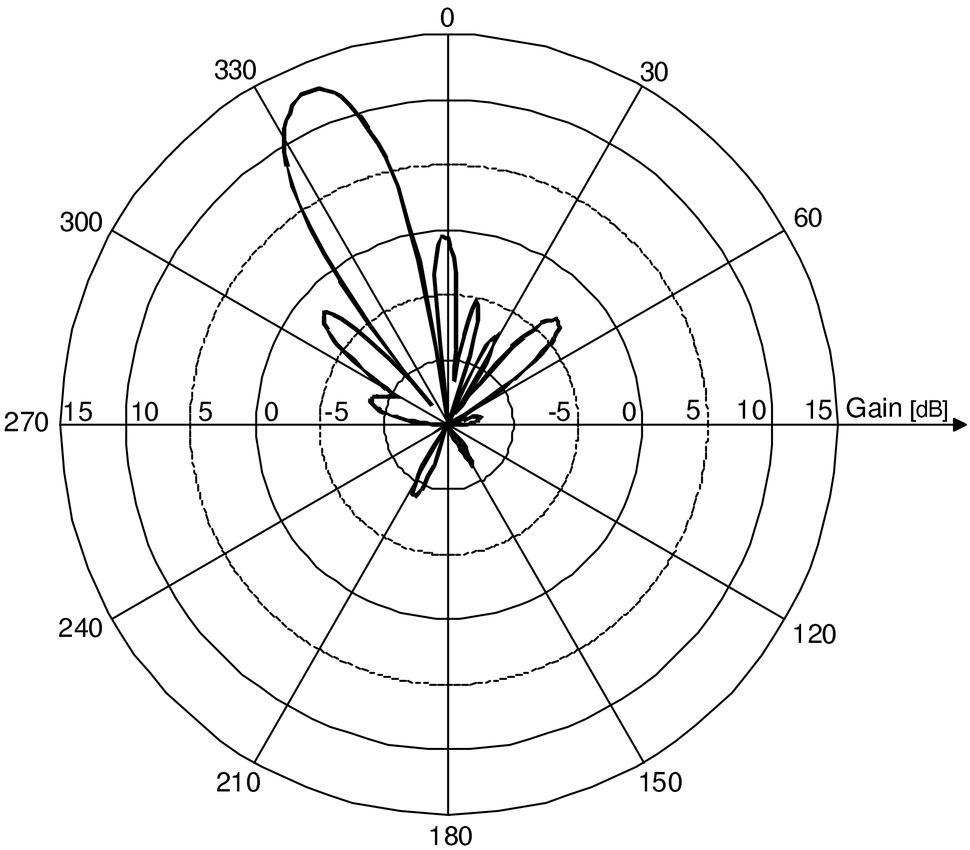


Figure A.3: 2L f = 2.45 GHz

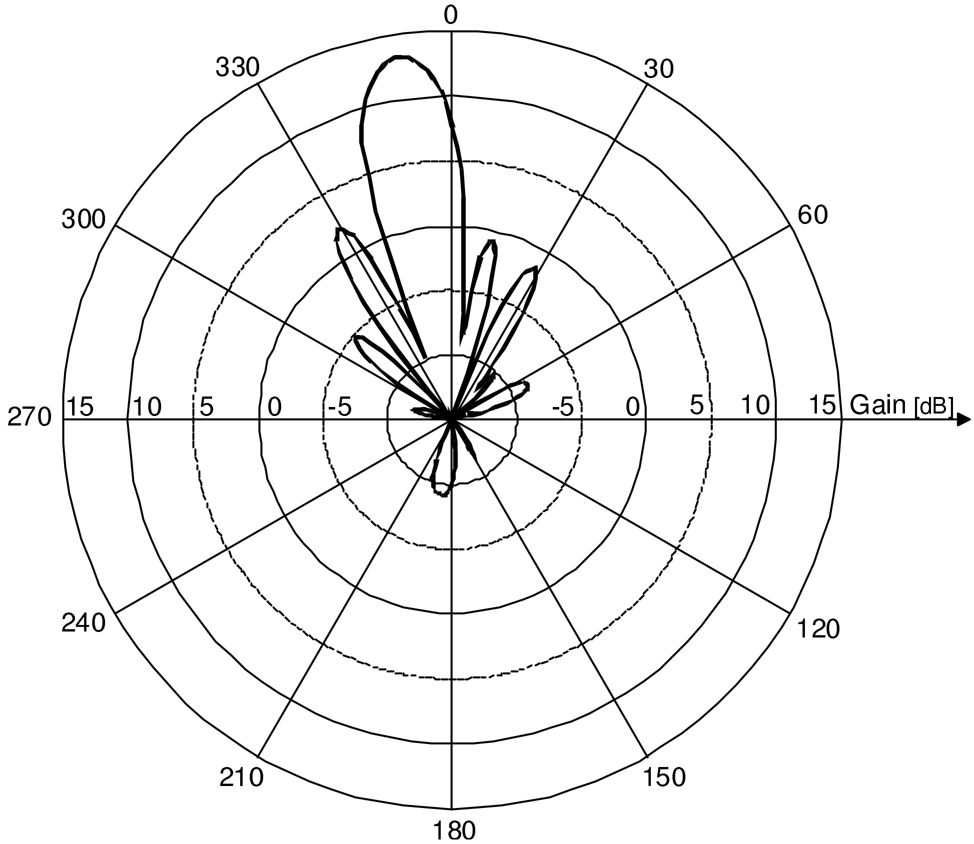


Figure A.4: 1L f = 2.45 GHz

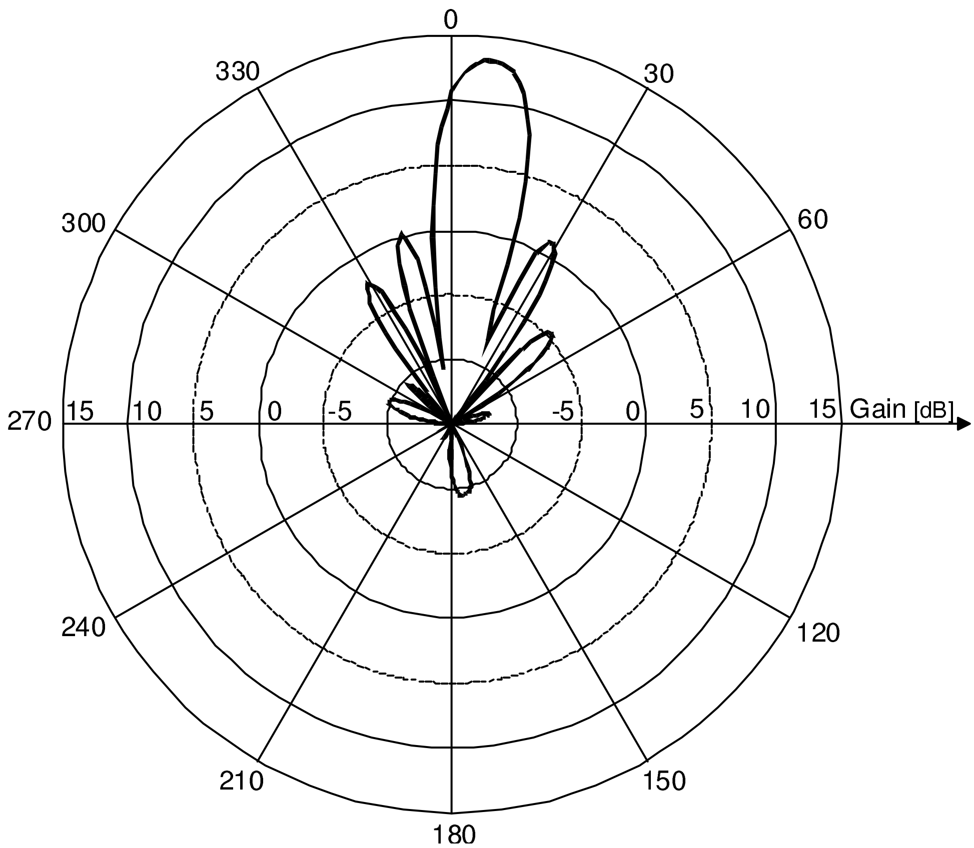


Figure A4: 1R f = 2.45 GHz

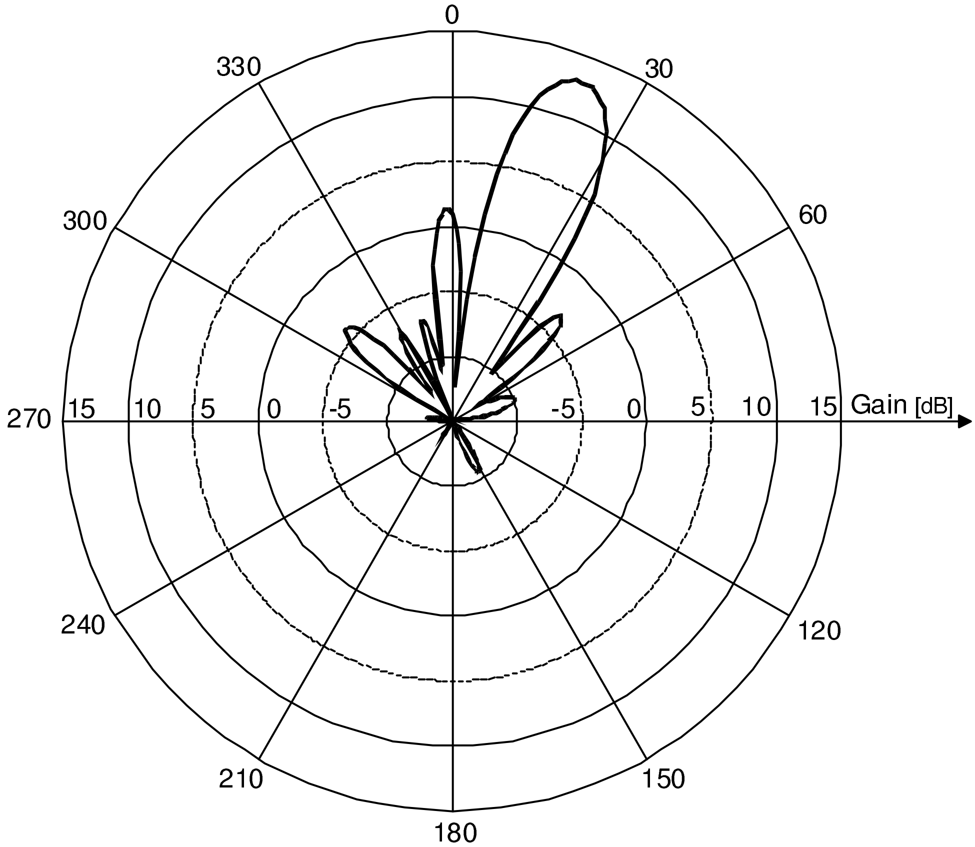


Figure A.6: 2R $f = 2.45$ GHz

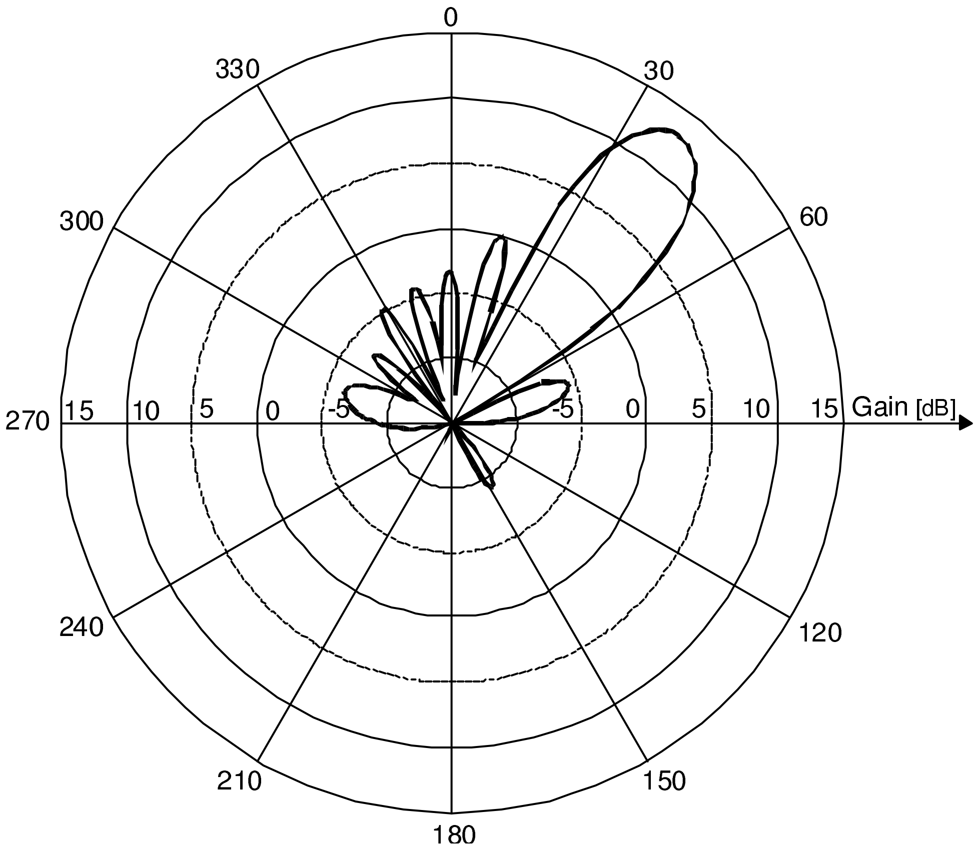


Figure A.7: 3R $f = 2.45$ GHz

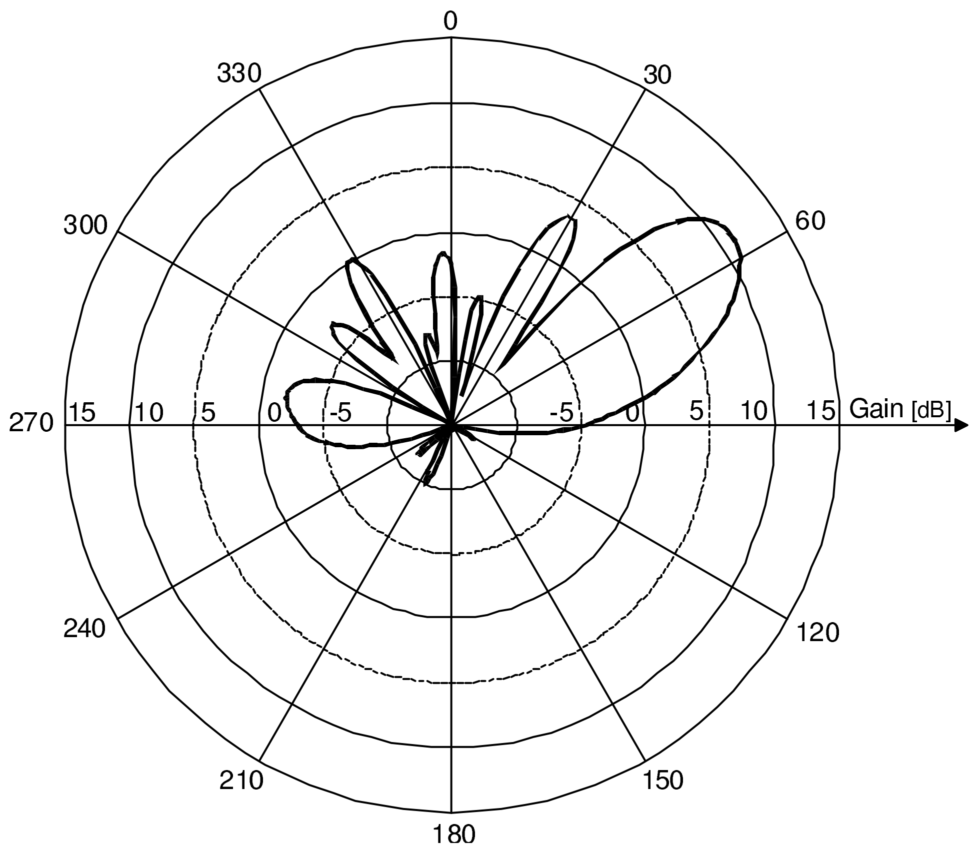


Figure A8: 4R f = 2.45 GHz

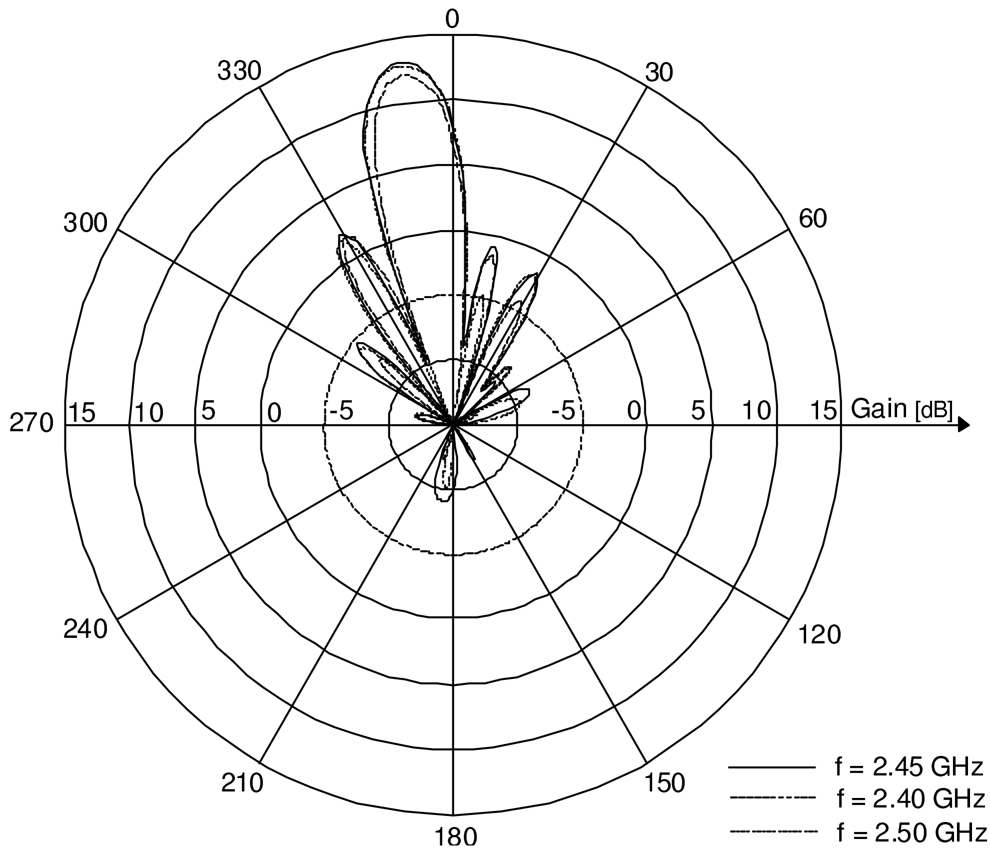


Figure A.9: 1L

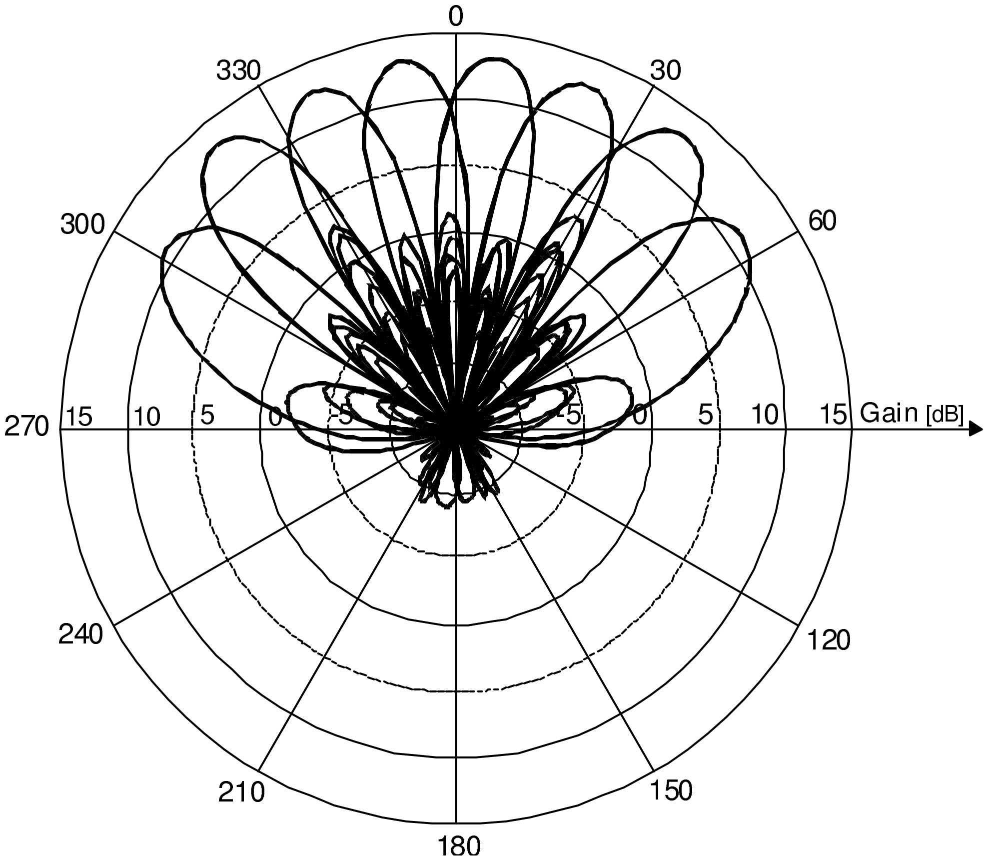


Figure A.10: Simultaneously f = 2.45 GHz

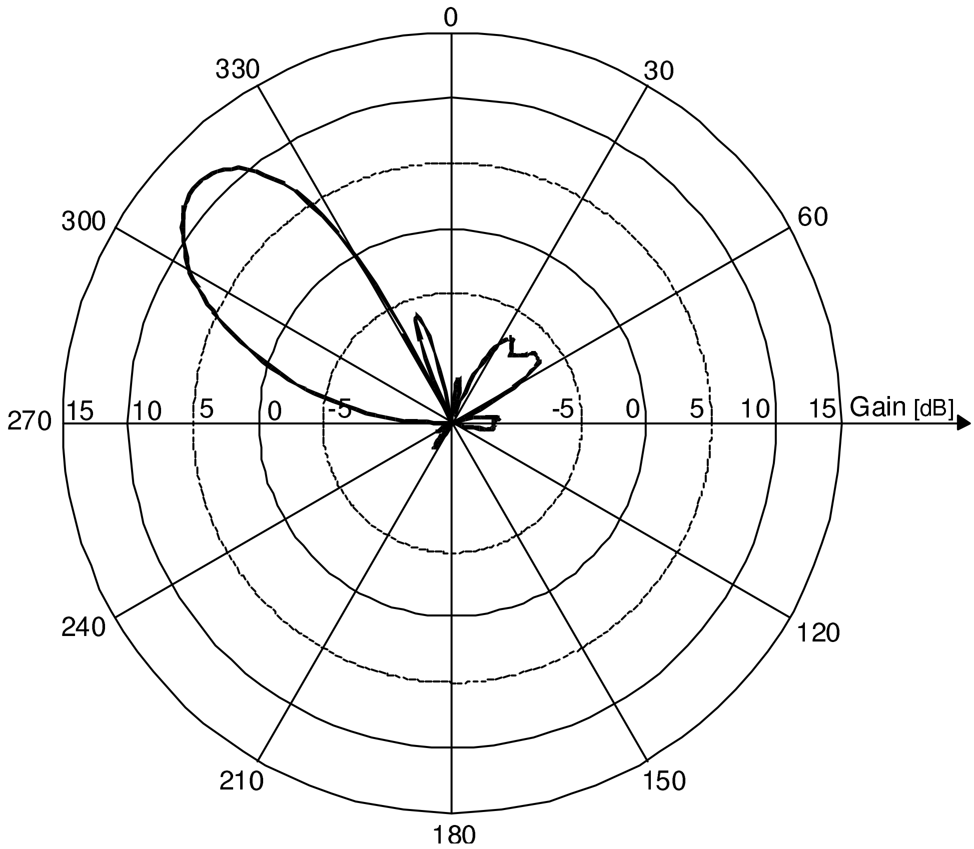


Figure A.11: L3+L4 f = 2.45 GHz

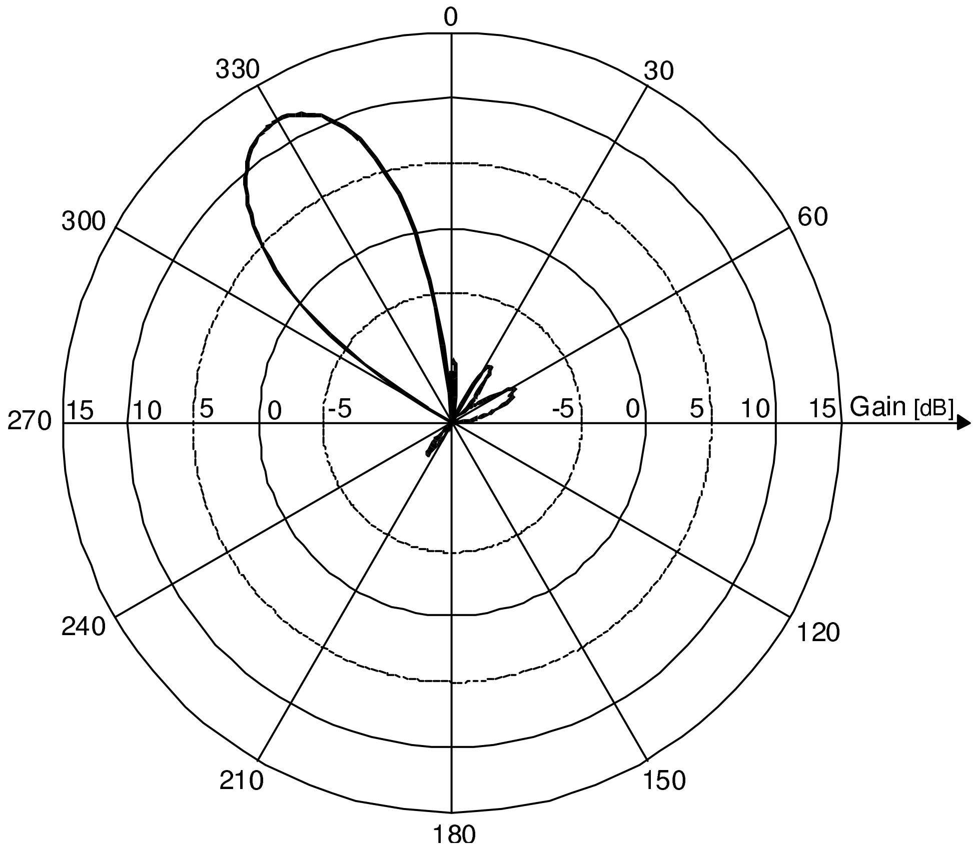


Figure A.12: L2+L3 $f = 2.45$ GHz

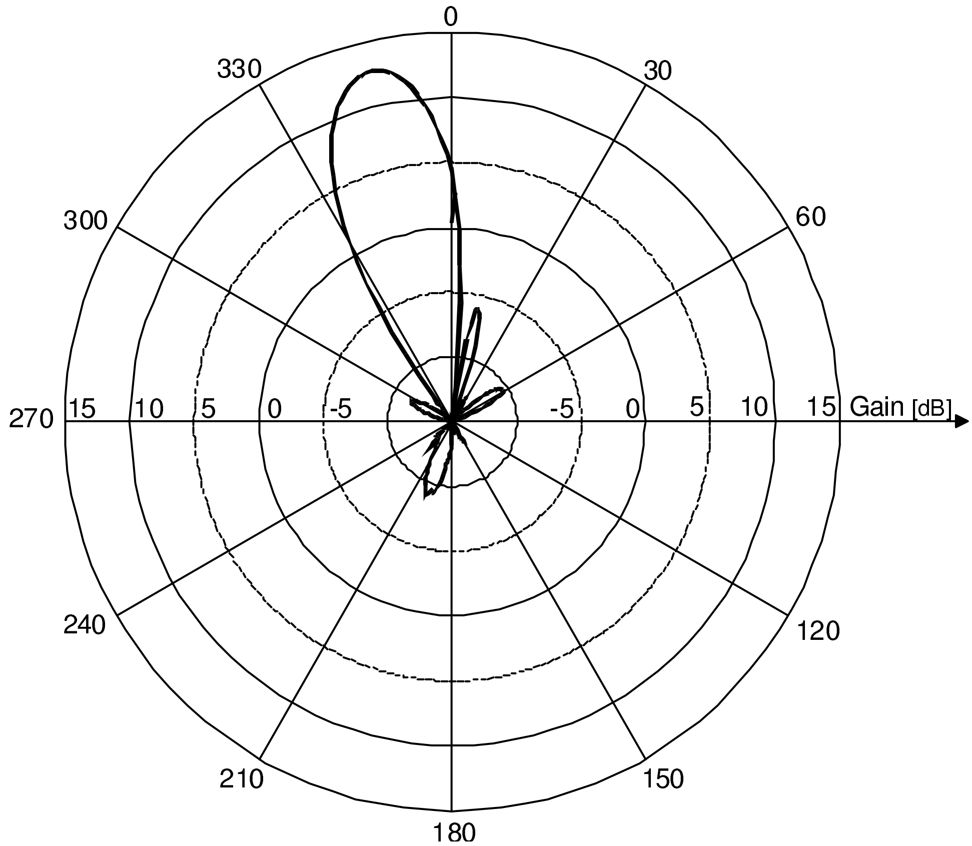


Figure A.13: L1+L2 $f = 2.45$ GHz

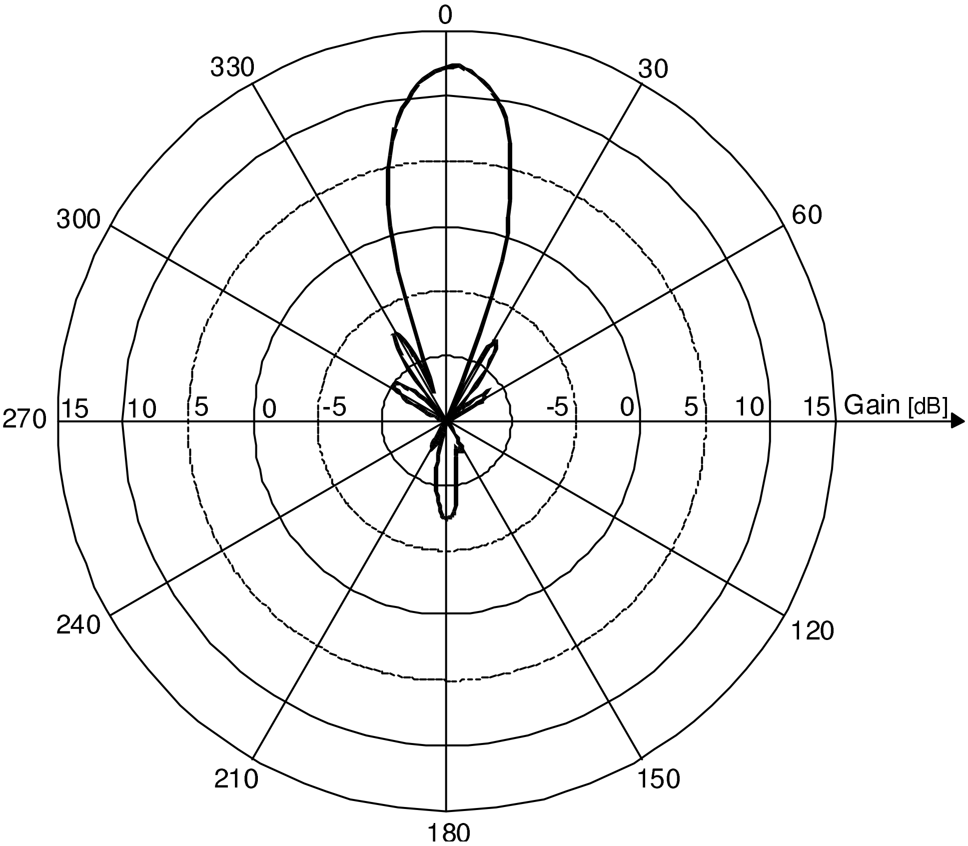


Figure A.14: L1+R1 f = 2.45 GHz

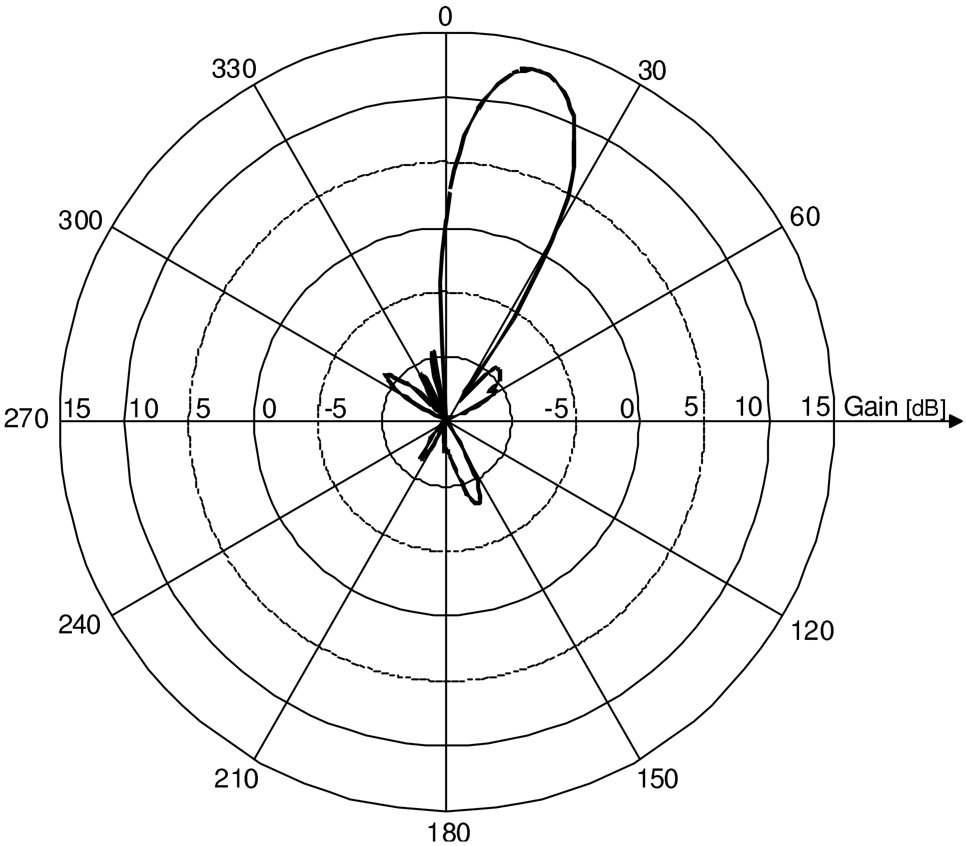


Figure A.15: R1+R2 f = 2.45 GHz

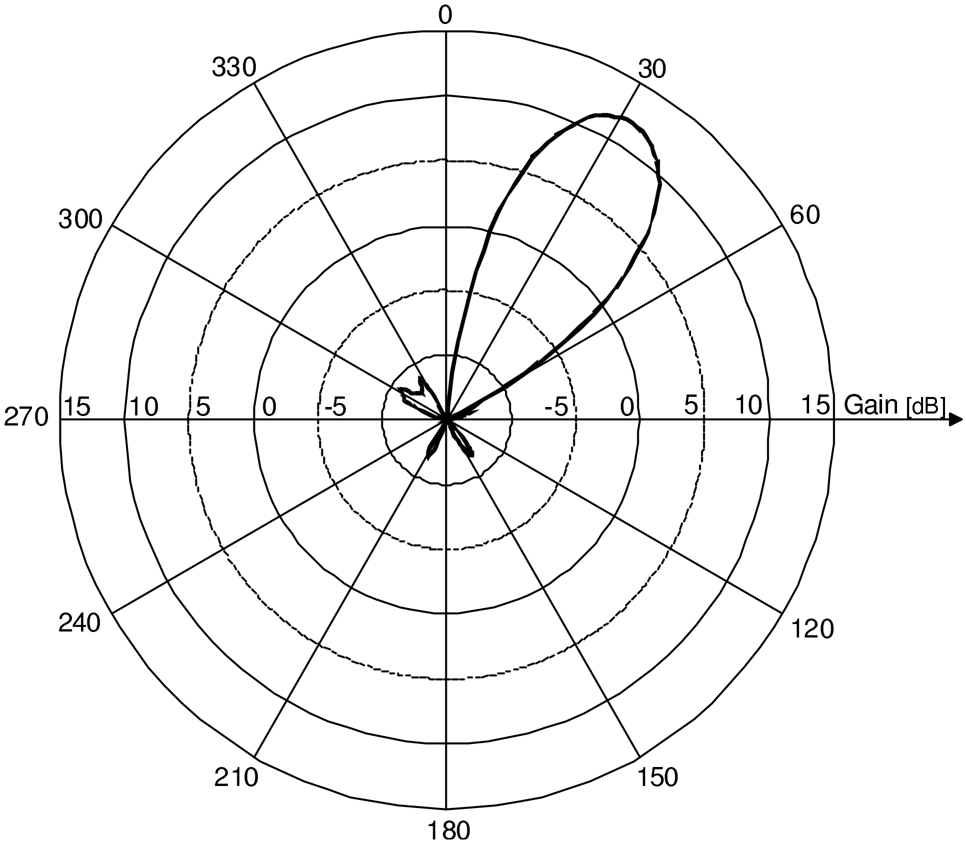


Figure A.16: R2+R3 f = 2.45 GHz

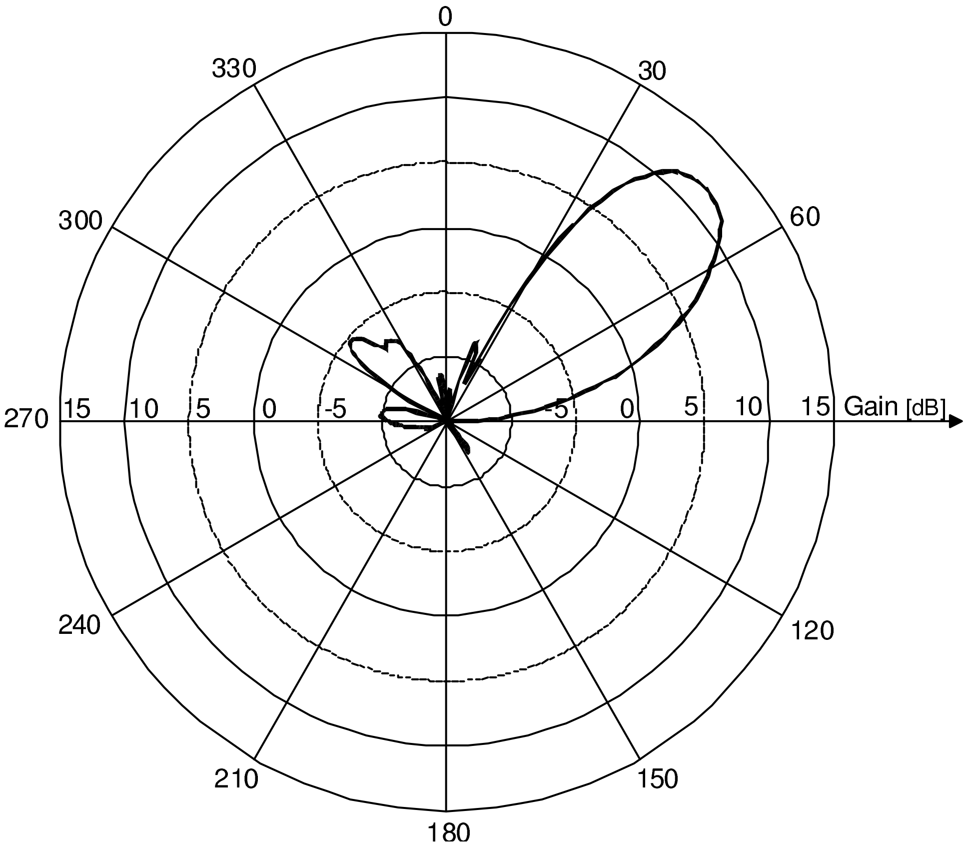


Figure A.17: R3+R4 f = 2.45 GHz

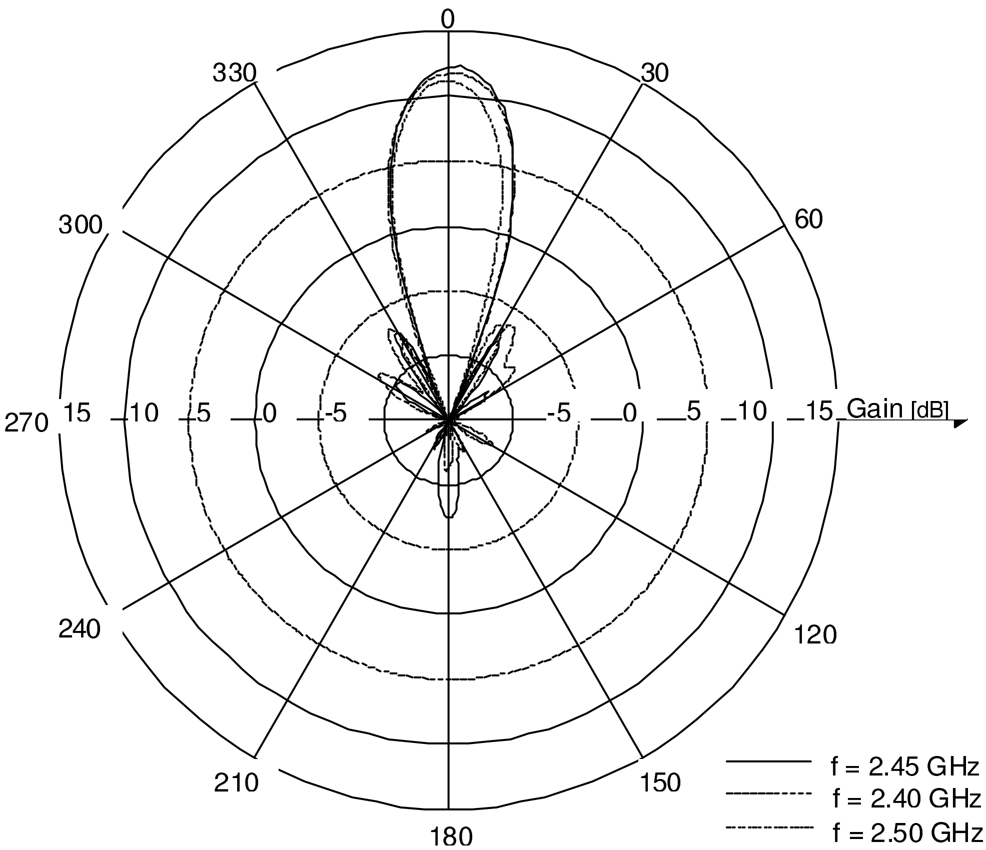


Figure A.18 L1+R1

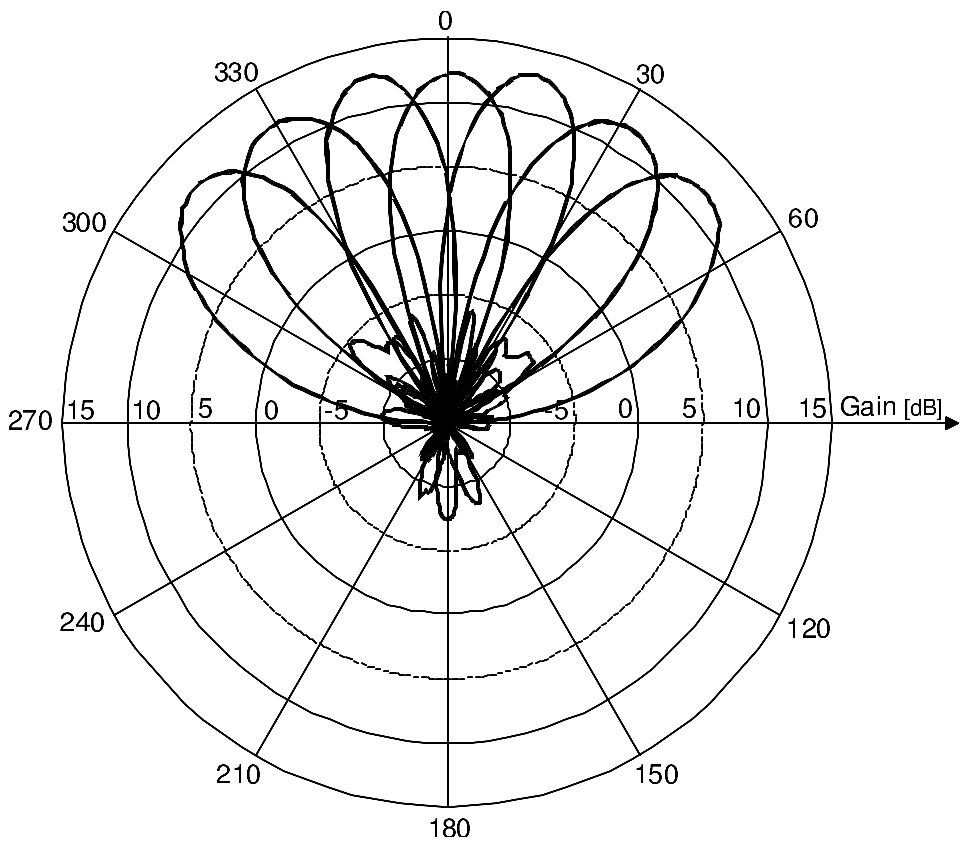
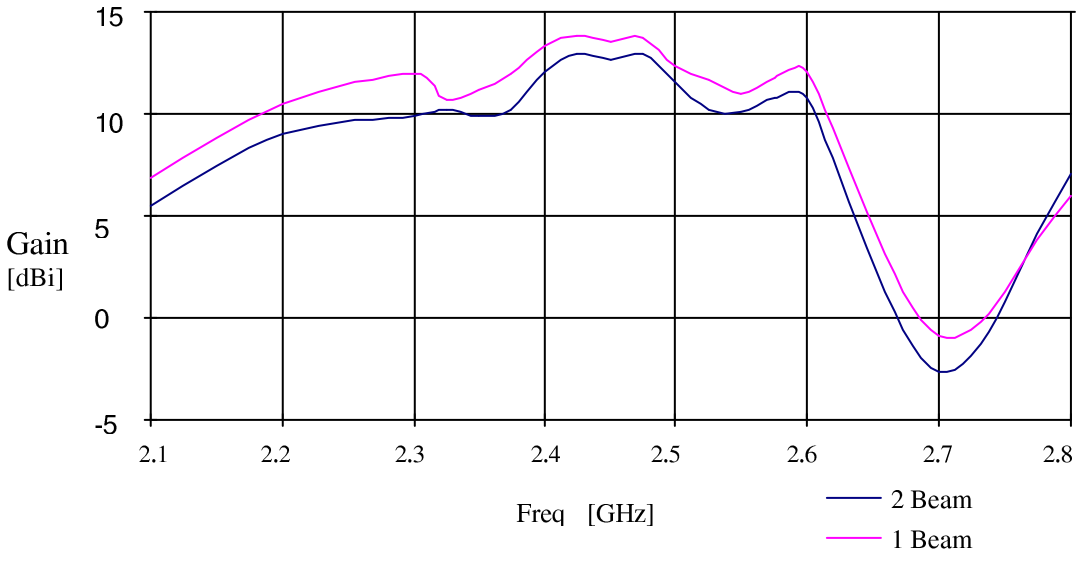


Figure A.19: Simultaneously $f = 2.45$ GHz


15
10
5
0
-5
Gain
[dBi]
2.1
2.2
2.3
2.4
2.5
2.6
2.7
2.8
Freq [GHz]
2 Beam
1 Beam