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TNO report

TNO-DV1 2005 A036

Investigation on Antenna Configurations for Single Radar Applications

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Investigation on Antenna Configurations for Single Radar Applications

Probleemstelling

Een zogenaamd, qua afmetingen, schaalbaar en multifunctioneel RF (SMRF) systeem is een concept dat toepassing van radarsystemen op varende platformen op een aantal vlakken voordelig kan maken, bijvoorbeeld als het gaat om plaatsingsruimte en signatuur maar vanwege de modulaire structuur ook als het gaat om onderhoud- en ontwikkelingskosten. Er is een aantal manieren om een radarsysteem multifunctioneel en schaalbaar te maken. In dit project zijn de mogelijkheden, de meerwaarde en de haalbaarheid onderzocht om de volgende generatie radarsystemen van de KM te baseren op dual-band antennes c.q. wide-band antennes. De hieruit voortgekomen bevindingen zijn in het rapport TNO-DV1 2004 A212 beschreven. Voor het toepassen van meerdere functies binnen een enkele apertuur zijn behalve significante technologische vooruitgang ook afwegingen op systeemniveau benodigd om te kunnen bepalen of het concept in potentie kosten kan besparen. Dit laatste met behoud van de vereiste systeemcapaciteiten, Dit is een lang en complex proces, daarom is onderzocht welke soorten stralers in aanmerking komen om toegepast te worden in antenne-arrays voor enkelvoudige radarfunctionaliteit. Het antennesysteem dat uiteindelijk wordt toegepast hangt o.a. af van de eigenschappen en de missie van het plaatsingsplatform. Deze eigenschappen bepalen de uiteindelijke fysieke afmetingen en het gewicht van het antennesysteem. De doeleinden bepalen het al dan niet mechanisch scannen van de antennebundel, het operationele frequentiegebied, de polarisatie en bijvoorbeeld de maximaal haalbare scanhoek die gemaakt kan worden met de antennebundel.

Beschrijving van de werkzaamheden

Door TNO Defensie en Veiligheid, locatie Den Haag is een literatuurstudie uitgevoerd waarin is gekeken welke stralers goed kunnen worden toegepast voor de opbouw van een antenne-array voor het uitvoeren van de diverse radarfunctionaliteiten die binnen de KM van belang zijn. De geselecteerde stralers worden beschreven en beoordeeld op diverse voor een array-omgeving van belang zijnde parameters (zoals koppelingseffecten, scangedrag, bandbreedte). Voor de bepaling van het gedrag van deze parameters is geput uit gegevens die beschikbaar zijn in de open literatuur en zijn bovendien door TNO full wave veldberekeningen uitgevoerd als deze informatie ontoereikend of in zijn geheel niet beschikbaar was. Algemene eigenschappen en voor- en nadelen zijn ruimschoots behandeld evenals te nemen maatregelen om scanhoek- en bandbreedtebeperkende effecten als mutuele koppelingen en oppervlaktegolven tegen te gaan.

Resultaten en conclusies

Dit rapport beschrijft de uitkomsten van de gedane literatuurstudie, en geeft krachtig de karakteristieken weer van een zevental stralers die voor plaatsing binnen een antenne-array met enkelvoudige radarfunctionaliteit (array-bandbreedte rond de 20%) het best toepasbaar kunnen zijn. De uiteindelijke stralerkeuze is afhankelijk van de precieze radartoepassing die men voor ogen heeft en de eisen die men stelt aan bijvoorbeeld budget, systeemvolume etc. Dit zal altijd gepaard gaan met een trade-off tussen de verschillende (niet zelden tegenstrijdige) systeemeisen. Voor toepassing van het concept systeemintegratie is een belangrijke voorwaarde dat de stralers op planaire technologie zijn gebaseerd.

Toepasbaarheid

Het uit deze studie voortgekomen rapport kan ter oriëntatie worden gebruikt voor onderzoek aan en/of ontwikkeling van antennesystemen die gebruikt worden voor een enkele frequentieband. In het bijzonder geeft het rapport inzicht in de aspecten die een rol spelen bij het plaatsen van de behandelde stralers in een array-omgeving. De bijbehorende referentielijst kan prima dienen als informatiebron voor uitgebreider onderzoek.

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Abbreviations

TNO	Netherlands Organisation for Applied Scientific Research
BALUN	BALanced-to-UNbalanced
EBG	Electromagnetic Band Gap
LSLA	Long Slot Line Array
PCB	Printed Circuit Board
RCS	Radar Cross Section
SMRF	Scalable Multifunction Radio Frequency
MTBF	Mean Time between Failures
MTTR	Mean Time to Repair
RF	Radio Frequency
ESM	Electronic Support Measures
ECM	Electronic Counter Measures
CEC	Co-operative Engagement Capability

1 Introduction

The proliferation of advanced sensor and communications systems aboard military platforms has led to an increasingly large number of associated antenna systems. Onboard a ship one may encounter over 100 antennas and this number is expected to increase as new systems are added. In order to reduce costs and improve system characteristics such as Radar Cross Section (RCS), the idea of combining multiple functions into a single aperture becomes tempting. Applications for shared apertures include radar, satellite communications and electronic warfare.

This report is the second document resulting from the work done in the project 'Dual-Band Antennas' which is part of the V053 Radar Program. The goal of this project is to find the type(s) of radiator(s) that could fulfil the requirements for radar applications to be performed by a scalable multifunction radio-frequency (SMRF) system. Such a SMRF system is a direct result of the demands already described. The antenna used in a SMRF system could be constructed by the combination of different radiators, or by composing it of one radiator type that operates according to specifications for each desired application.

In the first document written for this project (report nr. TNO-DV1 2004-A212) the focus was exactly on an antenna system that performs multiple functions from a single aperture. It might be clear that opposing aspects like *system amount increase* and, space *and weight constraints becoming more stringent* have created a strong desire for shared aperture antennas. These are a new class of phased array antennas that combine the functionality of several antennas into one aperture using wideband multiple beam technology. Wide (10:1) bandwidth phased array antennas are needed to accomplish this goal. The current state of the art of broadband phased arrays is approximately 3:1 bandwidth, which is not adequate to support the wide range of applications mentioned earlier.

The implementation of such apertures may potentially reduce platform costs by prorating expenses over all functions using them. However, significant technological advancement is needed, and system-level trade-offs must be investigated in depth to determine if potential cost savings can be realised while maintaining required system capabilities.

Combining the functionality of several antennas into one shared aperture implies the simultaneous requirements for wide bandwidth, multiple polarisations, and multiple beams. These present a significant technical problem and challenges like state of the art in radiating element technology, monolithic microwave integrated circuit transmit/receive technology (demands state of the art in filters, diplexers and amplifier linearity), and array design (architecture: number of channels in the T/R modules, complexity of the beam forming networks).

In the first document it was concluded that ultra-wide band radiators are not an option for such antenna systems. A decade bandwidth array imposes unique requirements that are not usually encountered in a narrow band or wide band design (e.g. to perform a single function). The most fundamental array constraint is lattice spacing, which is limited to one-half wavelength (when imposing scanning capabilities this dimension will be even more restricted) at the highest frequency in order to avoid the appearance of grating lobes. This means automatically that the spacing at the lowest operating frequency is reduced to about 5% of the wavelength. The packaging of the accompanying T/R modules for a 10:1 system becomes impractical, therefore new architectures have to be developed.

Another option to have some multifunctionality from a single aperture could be found in the concept of interleaving arrays operating at different frequency bands. Concerning this it was concluded that no more than two frequency bands should be combined in order to meet most of the system requirements. Dual-band antenna arrays are feasible but solving their inherent problems will demand significant effort and cost. For that reason, at the present time, the added value for dual-band antenna arrays compared to the systems available on naval platforms now, is negligible.

Antenna arrays designed to perform over a single frequency band are for now the best alternative to construct radar systems that will answer most satisfying to the functional requirements. Additionally, it was recommended to redirect further investigation on the identification of radiating elements for such antenna systems.

The content of this report is concerned exactly with this orientation on radiators for antenna systems that operate a single frequency band only. For that goal use has been made of the radiator portfolio that had been set up in the first report. The radiator types have been complemented in this report with radiator configurations that where not thought of to be useful within the framework of the first report. Also the feeding networks necessary for these radiators have been described including the possibility to use electromagnetic band gap (EBG) structures in those networks to optimise the overall antenna efficiency.

In chapter 2 a categorisation is made of all the radiators that are considered in this document. Subsequently, the categories are described and possible feeding structures for antenna arrays are identified and explained.

The following chapter is concerned with the description and explanation of the radiators within each category and some words about their structural design and performance in an array environment.

Chapter 4 considers the treated radiators in a kind of recapitulation and gives some general comments.
The report is concluded in chapter 5.

2 Possible Solutions

2.1 Introduction

The radiator types that may fulfil the requirements of a radar system as given in the appendix in terms of its antenna system are presented here. There are three categories, i.e.:

1 Horizontal Printed Radiators;
2 Vertical Printed Radiators;
3 Aperture Radiators.

All categories will be treated hereafter.

2.2 Description of the Categories

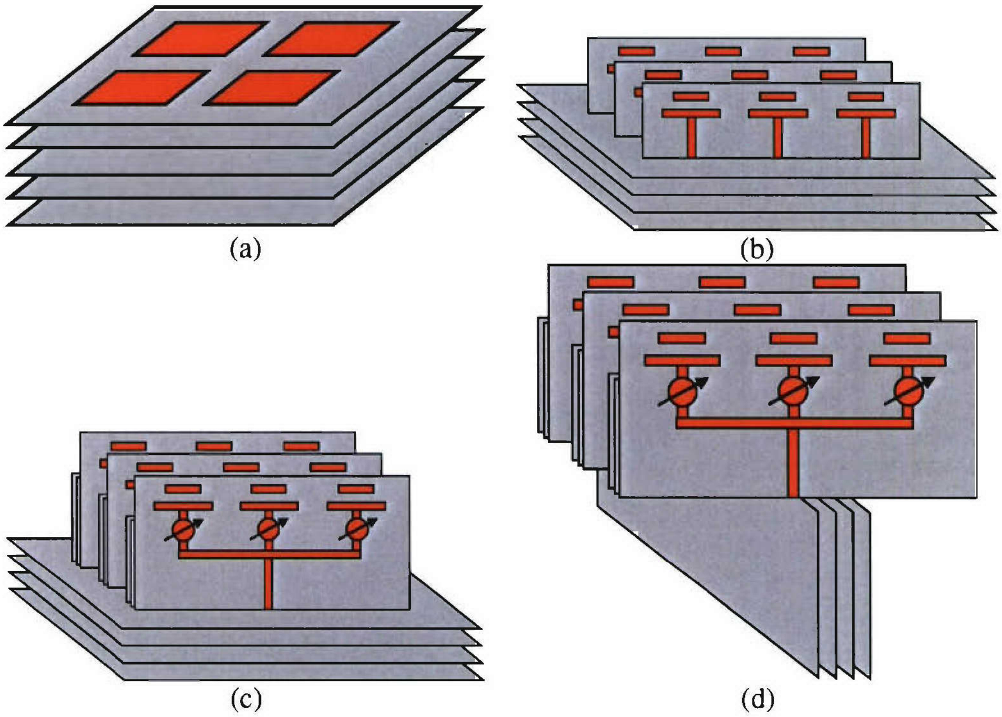
Category 1 and 2 contain radiators printed on planar single or multi-layer substrates. The orientation of the substrates within the array environment destinguishes the two categories. The antennas in category 1 are broadside radiating elements like microstrip patch antennas whereas the antennas in category 2 are end-fire radiating elements like T-dipoles or printed tapered notch antennas.

Apart from the radiators themselves, there are two more topics that have to be addressed when talking about printed integrated arrays. One topic deals with mutual coupling and in particular with scan blindness and active return loss. When using standard radiators in a large scanning array environment usually special measures have to be taken to reduce the mutual coupling. If the radiators are printed on a common substrate, surface waves travelling inside the substrate can cause critical mutual coupling effects, whereas if the radiators are printed on separate substrates the direct mutual coupling may be very high. In case of radiators printed on a common substrate the mutual coupling can be reduced by EBG structures or other blocking configurations like slots milled in the substrate or the ground plane. The mutual coupling between radiators on separate substrates can be reduced by metal fences between them.

The second topic that has to be addressed, deals with parallel plate modes in multi-layer feeding circuits. Parallel plate modes can be excited very easily decreasing the overall efficiency and causing additional mutual coupling and resonances. They can be suppressed by carefully positioned plated via holes or by future types of EBG structures.

Depending on the radiator type (broadside or end-fire) several configurations for the combination antenna/feeding network can be imagined:

- Broadside radiating elements on top of planar multi-layer feeding structure (Figure 2.1a);
- Endfire radiating elements.
  - Separate elements partially on similar substrates connected to a planar multi-layer feeding network (Figure 2.1b).
  - Partially vertical and horizontal multi-layer feeding network (Figure 2.1c).
  - Combination of two vertical multi-layer feeding networks (Figure 2.1d).



(a) (b) (c) (d)

Figure 2.1 Array configurations based on printed planar substrates.

Each radiator type in category 1 and 2 should be combined with special measures to decrease the mutual coupling and the excitation of unwanted guided waves. In general the active return loss of the radiating elements has to be optimized over a certain scanning range. In case of broadside radiating antennas surface waves can be problematic and should be suppressed using EBG configurations. End-fire radiators can be decoupled by placing metal fences between vertical substrates or milling slots in the substrates. The excitation of parallel plate modes in the multi-layer feeding networks can be avoided by suppressing them locally with plated via holes or by future EBG like configurations.

The third category contains antenna elements that radiate via a certain aperture. There may be either a separate aperture for each antenna element (Figure 2.2a) or a common aperture that is excited by several elements together (Figure 2.2b). The performance of an array consisting of several separate apertures is expected to be similar to the performance of the arrays in category 1 and 2. Similar measures to isolate the array elements from each other may be used.

Arrays made up of apertures that are excited by several elements are different. The mutual coupling between the antenna elements is used to achieve a low active reflection coefficient. Measures to isolate the elements from each other are not needed and would be even disadvantageous. This type arrays are believed to have very broadband and wide-scanning properties.

In case the feeding network is realised in multilayer printed technology, the same measures as in category 1 and 2 have to be applied to suppress parasitic parallel plate modes.

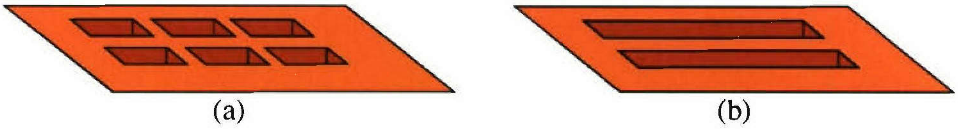


Figure 2.2 Array configurations based on aperture radiators.

It is relatively simple to design an array with a certain bandwidth if it is not required to scan. But maintaining this bandwidth over a large scanning angle (e.g. 0 - 60°) is very difficult. One option to improve the scanning properties of an array antenna is the use of a dielectric matching layer that covers the whole array aperture.

3 Review of Radiator Types

In this chapter the types of radiators that could be suitable to perform according to the system requirements in an array environment, are treated. For each radiator type an overview of its general characteristics will be given. Further, the radiator will be described more in detail and its performance will be outlined and evaluated.

3.1 H-Plane Sector Horn Antennas

General considerations:
- 1D array;
- One antenna per array element;
- Thick structure;
- Heavy;
- No feeding network;
- H-field launcher for feeding the waveguide should be used and maybe has to be designed;
- Phase centre varies over frequency;
- Mutual coupling to direct neighbour may be as high as -15dB but decays rapidly with increasing distance;
- Difficulties with level of active reflection coefficient during scanning can be expected.

This radiator type belongs to category 3 of section 2 (Figure 2.2a). Due to its flared aperture, it is suited for one-dimensional arrays only.
There is very little literature available on linear arrays of H-plane sector horn antennas. There are some references on the mutual coupling between two horns [1], on rectangular arrays of pyramidal horns [2], and on some pointing arrays of box-horns [3], [4]. Nevertheless, due to the wide-band character of horn antennas and the rapidly decaying mutual coupling with respect to distance, the chances of designing an array of H-plane horns with the high scanning and bandwidth requirements are believed to be very high. The good performance of such a horn antenna array however must be paid with a its high profile. The results shown in Figure 3.1 of a first investigation indicate that the design of an array with an active return loss smaller than -10 dB over a scanning angle range from 0° to 50° should be feasible without any problems. It should be possible to improve the level of the active return loss.

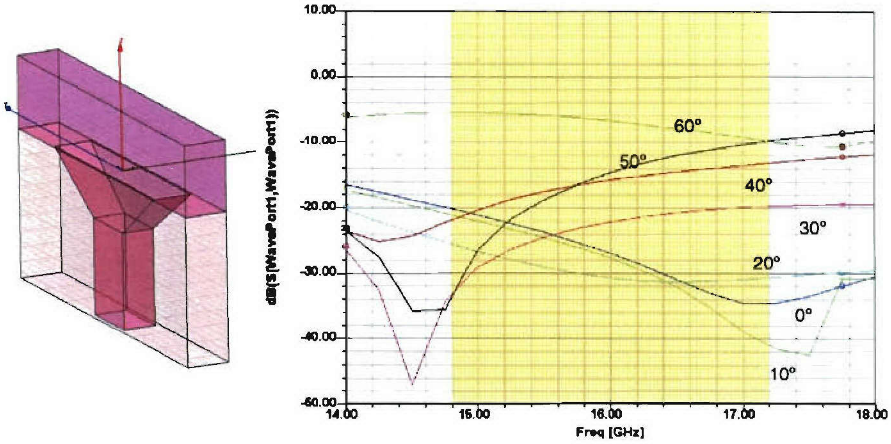


Figure 3.1 Unit cell of H-plane sector horn array and active reflection coefficients for several scanning angles as computed in a high frequency simulator.

Advantages:

1 Natural steep roll-off frequency behaviour at the lower frequency end of the usable band;
2 Simple element;
3 High power handling;
4 Low loss;
5 No need for complicated feeding network;
6 Behaviour well known and well described in published reports.

Disadvantages:

1 Variable phase centre with frequency;
2 Voluminous;
3 Heavy.

3.2 Stacked Patch Antennas

General considerations:

- 10dB Bandwidth up to 35% possible;
- Light weight;
- Thin structure;
- Surface waves may degrade the scanning performance;
- Special measures for de-coupling of sub-arrays (e.g. EBG, cavity-backed, non-continuous ground plane);
- Many layers.

This radiator type belongs to category 1 of section 2 (Figure 2.1a).
Simple printed microstrip patch antennas on single layered substrates consist of microstrip resonators of rectangular, triangular, or circular shape. Standard feeding configurations are:

- Probe-fed (co-axial cable from the back-side);
- Direct or monolithic feeding (microstrip line directly attached to patch);
- Electromagnetic coupled feeding (microstrip line reaching between patch and ground plane);
- Aperture-fed (slot in ground plane under patch fed by microstrip line).

Microstrip antennas are usually operated at their basic resonance frequency resulting in a broad hemispherical radiation pattern with linear polarisation that is good for using in an array environment. The bandwidth of patch antennas can be increased coupling two microstrip patches in a stacked configuration. The coupling is established via the electromagnetic filed. By increasing the total height of the printed antenna, its volume becomes larger, which is the main reason for the increased bandwidth. Unfortunately, due to the larger height, the mutual coupling between the closest neighbouring elements in an array environment increases as well. This tendency might be compensated by applying EBG technologies or cavity backing the individual radiators.

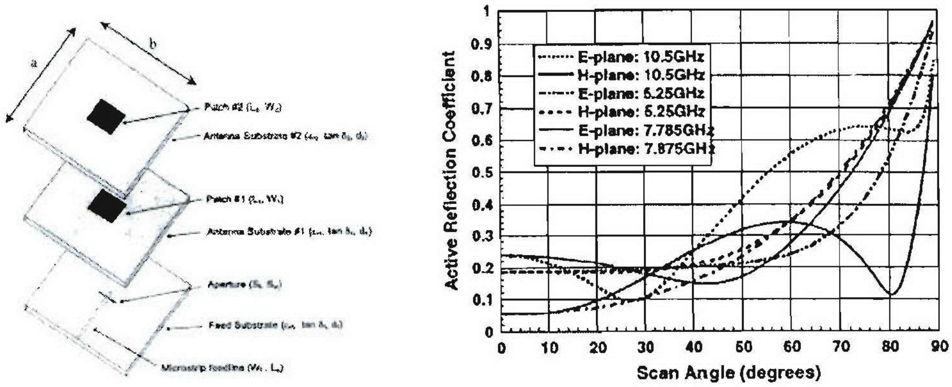


Figure 3.2 Stacked patch antenna [11].

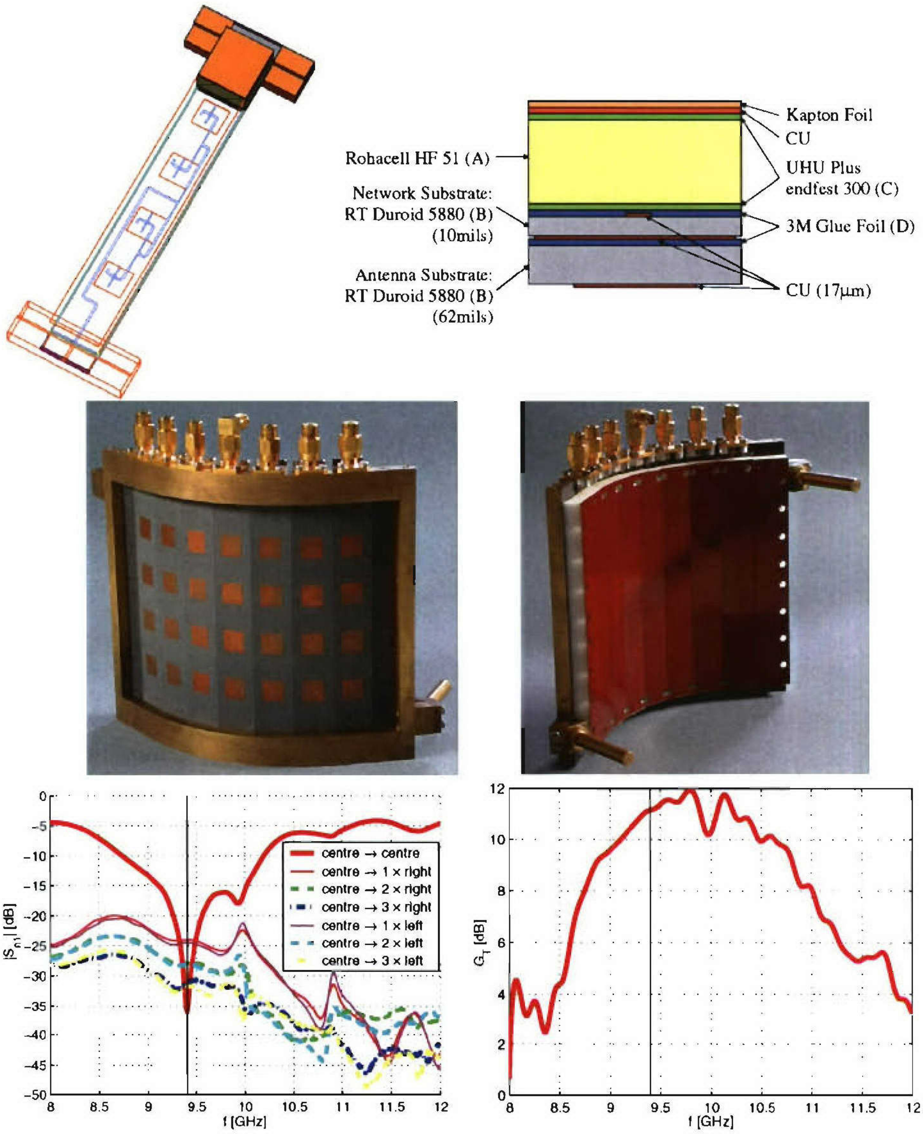


Figure 3.3 Sub-arrays of single layer patch antennas within a conformal array [13].

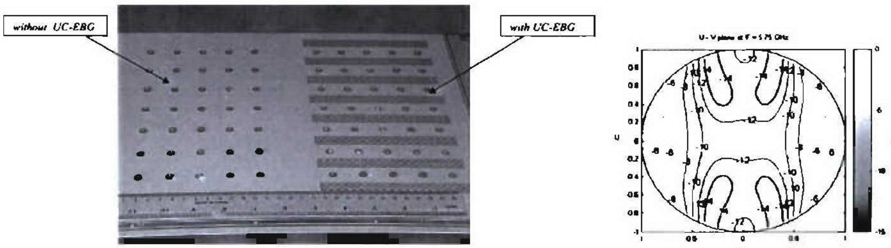


Figure 3.4 Single layer patch antennas separated by EBG structure [19].

Advantages:

1 Planar technology (low weight and easy to manufacture);
2 Simple broadband element;
3 Low profile;

4 One element can be used for both orthogonal polarisations;
5 Behaviour well known and well described in open literature.

Disadvantages:
1 Possible power loss and scanning degradation due to surface waves;
2 Maintenance might become problematic if array is etched on same layer structure.

3.3 Printed T-Dipole Antennas

General considerations:

- 10dB Bandwidth up to 40% possible;
- Light weight;
- Vertically oriented printed circuit boards (PCBs);
- Balanced-to-unbalanced (BALUN) transformer;
- Special measures for de-coupling of array elements.

This radiator type belongs to category 2 of section 2 (Figure 2.1b-d).
In contrast to printed antennas on infinitely extended planar substrates, which normally produce a broadside radiation pattern, Printed T-Dipoles are of the endfire type. They are etched on a planer substrate, which is finite in the direction of main radiation. The actual radiating element, the dipole, is etched close to the edge of the substrate and is oriented parallel to the edge. A microstrip line feeds the antenna. For a symmetric excitation of the dipole, a BALUN (balanced/unbalanced) transformer is needed. There are many possibilities to realise a BALUN structure.

- A centred slot between the two arms of the T-dipole is excited by a crossing microstrip line [24], [25], the foot of the T providing the groundplane for the microstip line. The centred slot can be considered as a slot line. Matching is achieved with the help of the stubs: the parallel stub located between the two horizontal arms of the T-dipole (slot), and the serial stub placed at the end of the microstrip line.

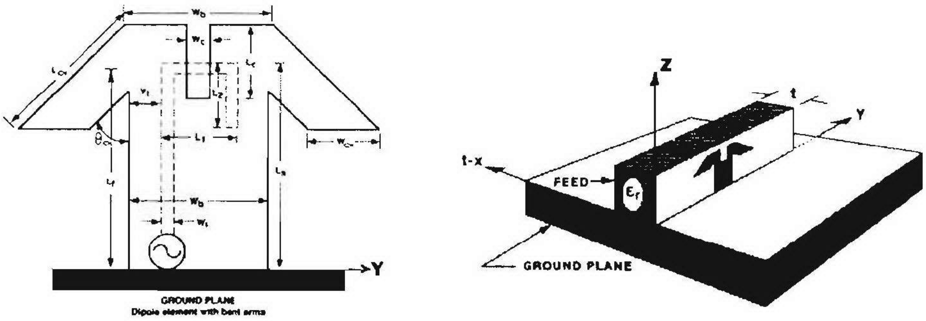
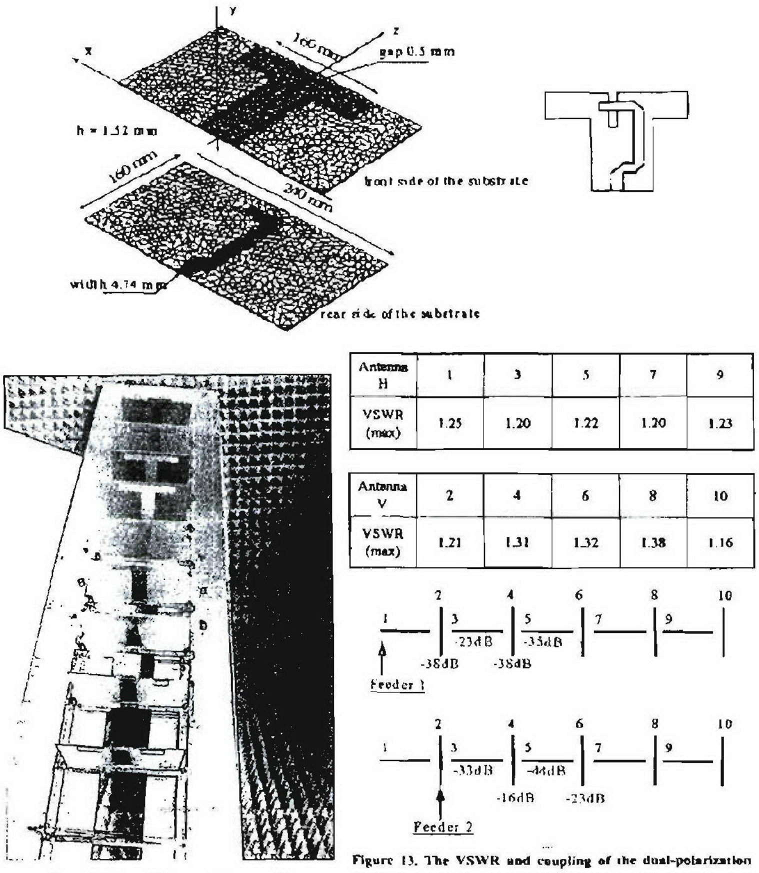


Figure 3.5 Printed T-dipole with bent-down arms fed via a microstrip-to-slot line BALUN [24].



Antenna H	1	3	5	7	9
VSWR (max)	1.25	1.20	1.22	1.20	1.23

Antenna V	2	4	6	8	10
VSWR (max)	1.21	1.31	1.32	1.38	1.16

Figure 7. A view of the array during assembly.

Figure 13. The VSWR and coupling of the dual-polarization antenna.

Figure 3.6 Simple printed T-dipoles fed via a microstrip-to-slot BALUN and their performance in an array [25].

- If a coplanar stripline feeds the dipole, a microstrip-to-coplanar stripline BALUN transformer can be realised by a 180° hybrid [26]-[28].

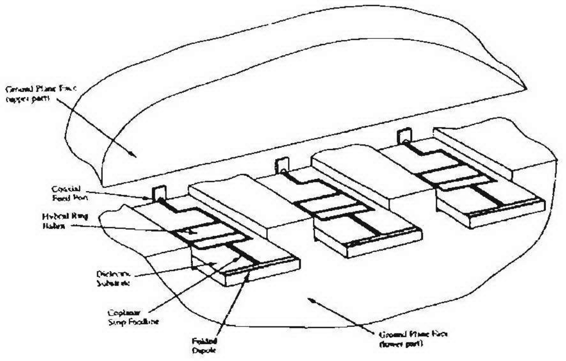
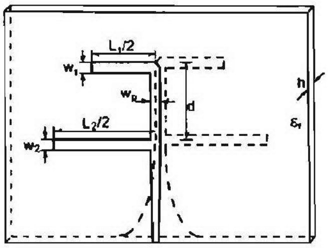
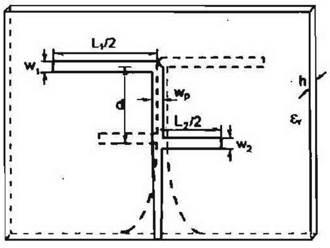


Figure 3.7 Printed T-dipoles fed via a microstrip-to-coplanar stripline BALUN [27].

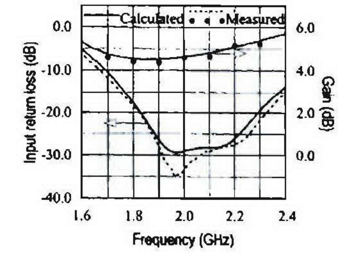
- In case a strip dipole configuration with both arms on opposite sides of the substrate has to be fed, a microstrip-to-parallel stripline BALUN can be constructed by gradually tapering the groundplane of the microstrip line [29].



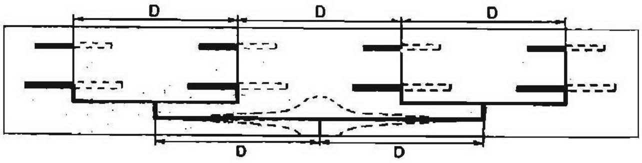
(a)



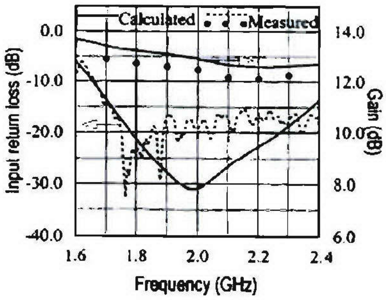
(b)



Measured and calculated input return loss and gain of the experimental broad-band antenna without reflector.



Configuration of a vertically stacked array of printed-strip dipoles with a corporate feed network of parallel striplines and tapered line transitions.



Measured and calculated input return loss of the array antenna of Fig 8.

Figure 3.8 Printed T-dipole fed via microstrip-to-parallel stripline BALUN [29].

The mutual coupling between the antenna elements in an array can be significantly reduced by placing metal fences between the elements.
TNO Defense, Security and Safety has some experience with linear arrays of printed T-dipoles. In the course of a numerical investigation a linear array was designed. To achieve a certain beamwidth in the plane perpendicular to the scanning plane, each array element consisted of a sub-array of four T-dipoles printed on the same substrate and fed by a fixed parallel feeding network. The array element is shown in Figure 3.9. Metal fences separate the array elements. They have the same height as the substrates of the T-dipoles. The 10 dB bandwidth of the array element is about 11% and the mutual coupling with the neighbouring element is about -14 dB. These values are not very satisfying but there is room for improvement. The bandwidth can be potentially increased by using T-dipoles with bent-down arms and it should be possible to further reduce the mutual coupling by making the fences slightly higher than the T-dipoles, which in the current design is not the case.

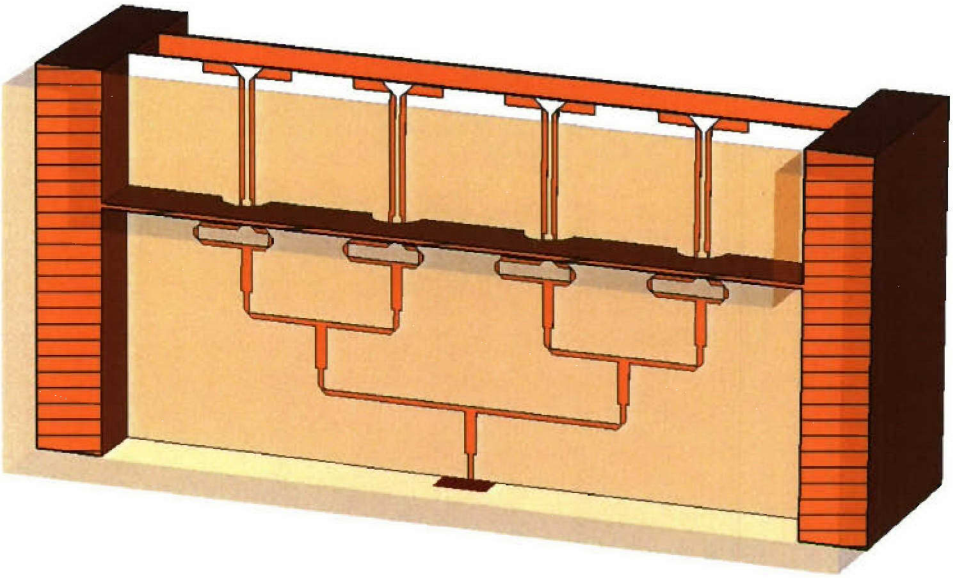


Figure 3.9 Array element (sub-array) designed at TNO Defense, Security and Safety.

Advantages:

1 Planar technology (low weight and easy to manufacture);
2 Simple element;
3 Stable pattern over its entire bandwidth;
4 Low cross-polarised components;
5 No problems regarding surface waves;
6 Good scanning properties;
7 Well known in open literature.

Disadvantages:

1 Medium high profile;
2 Needs one element per polarisation;
3 Supporting frame required due to vertical orientation;
4 Design of BALUN transformer for dipole-to-microstrip transition necessary.

3.4 Printed Quasi-Yagi Antennas

General considerations:

- 10dB Bandwidth up to 33% possible;
- Light weight;
- Vertically oriented PCBs;
- BALUN transformer;
- Special measures for de-coupling of sub-arrays.

This radiator type belongs to category 2 of section 2 (Figure 2.1b-d).
Printed Quasi-Yagi Antennas are an enhancement of the printed T-dipoles. A coplanar stripline-fed printed dipole serves as driving element in a Yagi configuration, exciting stongly a TE_0 surface wave that travels inside the substrate. An additional printed dipole being strongly coupled to the TE_0 surface wave is used as a director and the truncated ground plane of the microstrip feeding serves as a reflector for the TE_0 surface wave. A

BALUN transfomer may be realised by a power splitter and a 180°-delay line [33]-[37], by a 180° hybrid [38]-[39], or by a microstrip line crossing a slot line etched in its ground plane [40]-[42]. Quasi-Yagi Antennas are very broadband elements.

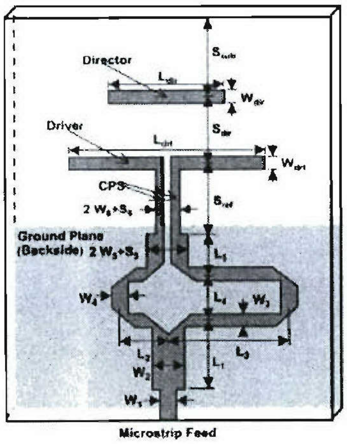


Figure 3.10: Printed quasi-Yagi antenna with microstrip-to-CPS line BALUN [33].

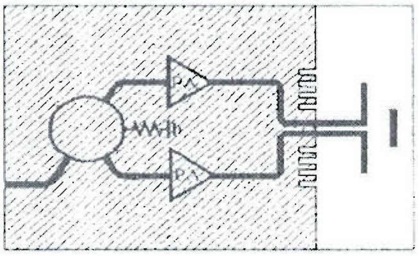


Figure 3.11 Printed quasi-Yagi antenna with push-pull amplifier [38].

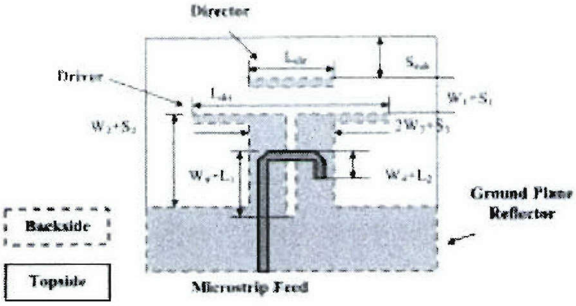
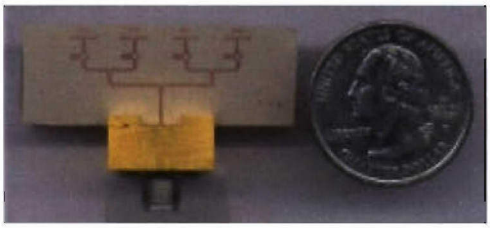
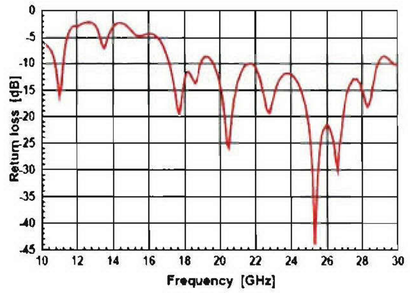


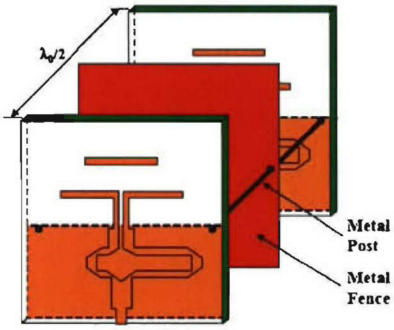
Figure 3.12 Printed quasi-Yagi antenna with microstrip-to-slot line BALUN [40].



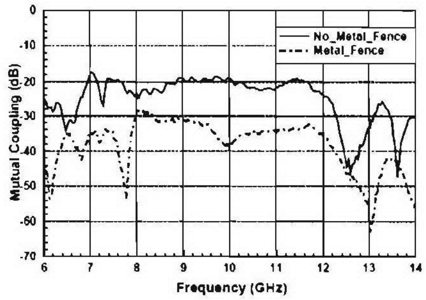
Photograph of K-band four-element quasi-Yagi array prototype.



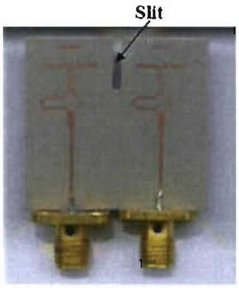
Measured input return loss of the K-band four-element array at 20 Ghz.



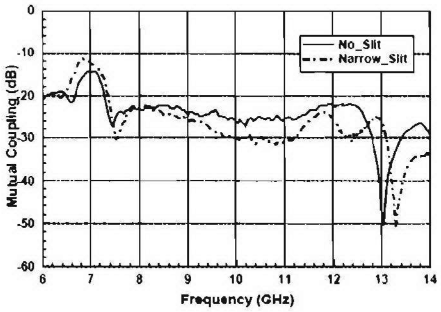
Reducing H-plane coupling between quasi-Yagi antennas using a metal fence.



Measured H-plane mutual coupling with and without the metal fence.



Two element quasi-Yagi array for E plane mutual coupling measurement.



Measured results of the effect of the slit on E-plane mutual coupling.

Figure 3.13 Application of printed quasi-Yagi antennas in arrays [43].

The mutual coupling between the antenna elements in an array can be significantly reduced by placing metal fences between the elements or, if etched on the same substrate, by milling slits in-between the single antennas.

Advantages:

1 Planar technology (low weight and easy to manufacture);
2 Low cross-polarised components;
3 Stable pattern over its entire bandwidth;
4 Pattern more directive with respect to the Printed T-Dipole;
5 Better mutual coupling with respect to the Printed T-Dipole;
6 No problems regarding surface waves.

Disadvantages:

1 Supporting frame required due to vertical orientation;
2 Smaller maximum scanning angle with respect to the Printed T-Dipole;
3 Needs one element per polarisation;
4 Medium high profile.

3.5 Printed Tapered Slot Antennas

General considerations:

- 10dB Bandwidth up to 5:1 possible;
- Light weight;
- Vertically oriented PCBs;
- BALUN transformer;
- Special measures for de-coupling of sub-arrays.

This radiator type belongs to category 2 of section 2 (Figure 2.1b-d).
Printed Tapered Slot Antennas also known as "flared notch" or "Vivaldi antennas" belong to the group of (theoretically) "frequency independent" antennas. The bandwidth of "frequency independent" antennas is limited in practice toward the lower frequencies by the size of the antenna and toward the higher frequencies by the precision of construction. Geometrically, frequency independent antennas are composed of a multiplicity of adjoining cells, each cell being scaled in dimension relative to the adjacent cell by a factor, which remains fixed throughout the structure. Since there will be always a smallest and a largest cell, the cells have to be designed to reduce the effects of the truncation of both large and small cells. To reduce the effect of the truncation of the large cells, the wave travelling from the excitation point along the structure must be attenuated before it encounters the end. Attenuation due to radiation is preferred but sometimes the use of lossy materials to attenuate the remaining power is necessary. Generally, at least one dimension of the largest cell must be approximately one-half wavelength in order to substantially eliminate the effect of the large-end truncation. On the other hand, the small cells have to be accurately scaled until their dimensions are a small fraction of the wavelength at the highest frequency of operation. The conductor configuration in each cell must be capable of providing means of propagating the electromagnetic wave from the feed point toward the larger cells at all frequencies.
The radiating structure of printed tapered slot antennas consists of a planar slot line running perpendicular toward the edge of a finite substrate. On approaching the edge, the width of the slot line is flared reaching a maximum at the edge. The frequency band covered by the antenna is limited by the maximum and minimum width of the slot. The shape of the flaring (e.g. linear, elliptic, exponential, logarithmic, parabolic, hyperbolic, etc.) determines the characteristic of the frequency response within the matched frequency band. A BALUN transformer is required when the antenna has to be fed by a microstrip line. Normally this transformer is realized by the microstrip line perpendicularly crossing the slot line [44]-[47].

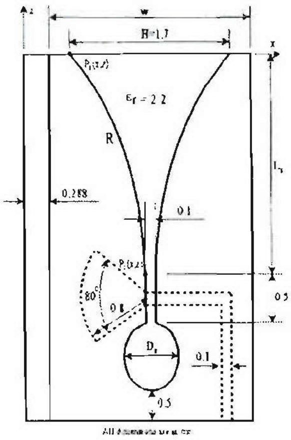
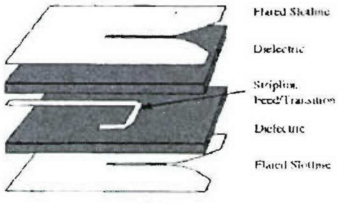


Figure 3.14 Exponentially tapered slot antenna with wide-band microstrip-to-slot line BALUN [45].



(a)

Figure 3.15 Tapered slot antenna with stripline feeding [46].

The matching is achieved by using two wide band stubs for each line type. The BALUN transformer limits the bandwidth of the antenna. Disadvantages of this antenna type are its high profile, the variation of its phase centre with respect to the operation frequency, the high cross-polarisation level outside the principal planes, and the excitation of higher order modes when used in an array environment. In a linear array configuration with all elements etched on the same substrate, the low frequency components will be "short-circuited" by the shunt patch of the adjacent element [49]:

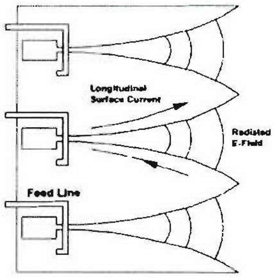


Figure 3.16 Monolithic E-plane array of tapered slot antenna.

The techniques applied to reduce these drawbacks limit the use of this antenna type in a dual polarised array environment.

To overcome some of the disadvantages of the standard tapered slot antenna, the so-called "bunny-ear" radiating element was developed [48]-[51]. The modifications include a different shape of the notch to reduce the height and the metallization close to the feeding has been etched out to enable a lower cut-off frequency. Adjacent elements in a linear array etched on the same substrate do not have a common metallization any more.

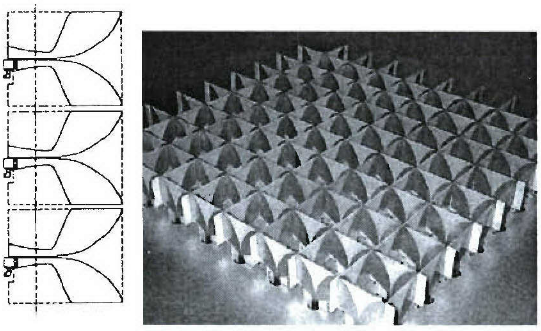


Figure 3.17 Two dimensional array of bunny-ear antennas [49].

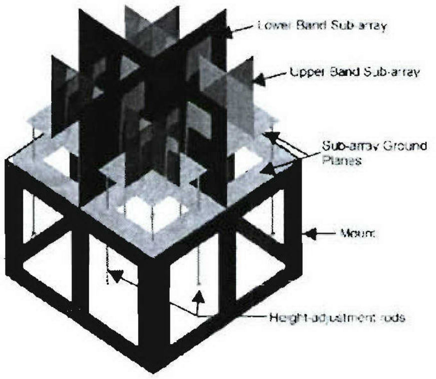


Figure 3.18 Two dimensional interleaved array of antipodal Vivaldi antennas [51].

The conventional tapered slot antenna has to be etched on one side of a substrate with a high dielectric constant in order to achieve a 50Ω impedance at the feed point. If a substrate with a lower dielectric constant has to be used, a different configuration called the "Antipodal Vivaldi" Antenna [52], [53] is beneficial. This kind of tapered slot antenna has one metallized branch of the radiator per side of the substrate and not both on the same side. Therefore, the feeding can be realised as a transition from a microstrip line to a parallel stripline constructed by gradually tapering the groundplane of the microstrip line. On the one hand this antenna has a very low cut-off frequency and on the other a relatively high cross-polarisation level. The cross-polarisation can be reduced by extending the geometry to a "Balanced Antipodal Vivaldi" antenna. This antenna used three metallized layers on two attached substrates. It is fed by a triplate microstrip line whose ground planes are tapered into two identical branches of the radiator. The central microstrip line merges into the other branch of the radiator. A symmetric set-up as described here has a very low cross-polarisation level. The mutual coupling between the antenna elements in an array can be significantly reduced by placing metal fences between the elements.

Advantages:

1 Very large bandwidth achievable;
2 Low weight;
3 Good scanning performance, absence of surface waves;
4 Stable radiation pattern;
5 Behaviour well known in open literature.

Disadvantages:
1 Needs one element per polarisation;
2 High cross-polarised component off the principal planes;
3 Phase centre varies over frequency;
4 Voluminous (quite high profile), larger bandwidth needs higher profile.

3.6 Periodically Excited Parallel Plate Waveguide

General considerations:
- Thick structure;
- Heavy;
- Mutual coupling is expected to be very strong but can be used to achieve a matching in the array environment.

This radiator type belongs to category 3 of section 2 (Figure 2.2b).
Parallel plate waveguides excited periodically by coaxially-fed monopole elements have been investigated theoretically and experimentally in [55]. The emphasis was on the use of this configuration as feeding structures for Rotman or other feed-through lenses. The application of the feeding structure for antennas consisting of open-ended parallel plate waveguides was considered in [58], [54], and [56]. The results presented in these publications show a potential for designing wide-band, wide-scanning arrays. This property might be improved by the application of dielectric sheets as matching layers as proposed in [57]. The material used for the matching layer typically has a low dielectric constant of about 1.3. The matching layer is positioned close to the feeding monopoles. An array antenna designed in this way can be seen in Figure 3.19.

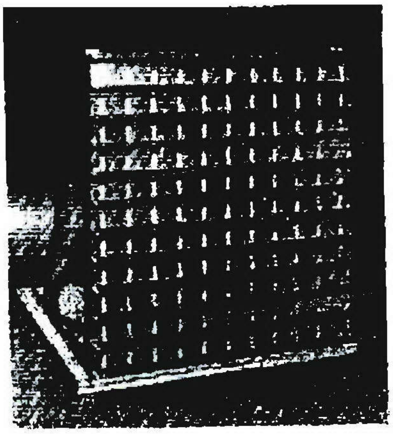


Figure 3.19 Array antenna consisting of several horizontally oriented, open-ended parallel plate waveguides fed periodically by monopoles.

In a linear array configuration using a single parallel plate waveguide with periodic excitations a desired aperture dimension perpendicular to the scanning plane of the array can be achieved by flaring the waveguide walls to the required width. A numerical investigation conducted at TNO Defense, Security and Safety on such a radiating structure has shown promising results. Performing a parameter study, the antenna has been optimized in an infinite array environment over the complete required bandwidth and scanning range (see Figure 3.20).

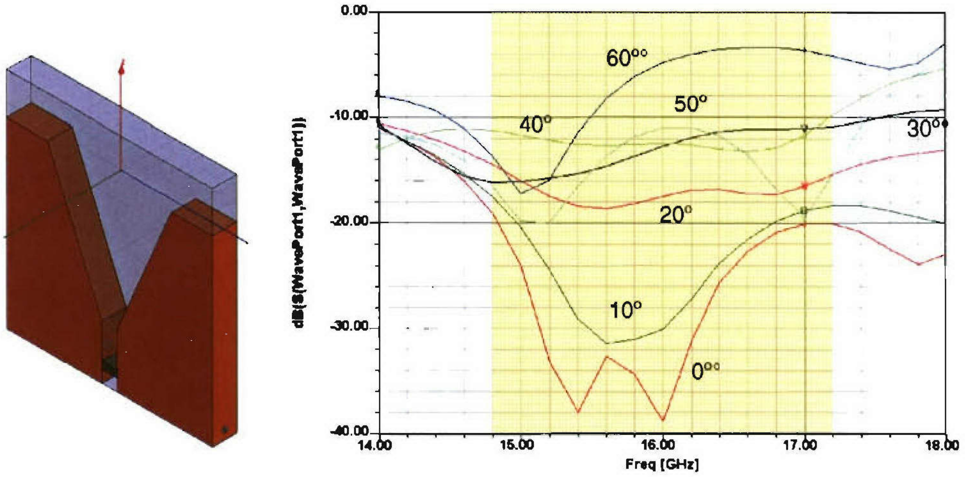


Figure 3.20 Unit cell of periodically excited parallel plate waveguide with flared aperture and active reflection coefficients for several scanning angles.

Advantages:
1 Simple element;
2 No feeding network;
3 High power handling;
4 Low loss;
5 Strong mutual coupling provides wideband behaviour.

Disadvantages:
1 Voluminous;
2 Needs matching layer for improved broadband wide angle scanning.

3.6.1 *Long Slot Line Array (LSLA)*

In a later stage during this investigation the existence of a derived version of the periodically excited parallel plate waveguide attracted the attention. This derived version is based on printed technology and is likely to achieve equal performance as the waveguide based one. It is known as the Long Slot Line Array (LSLA) and its concept has been treated in open literature [66]. The major advantage, with respect of the parallel plate waveguide, of this array element is its low profile, light weight and the possibility to be integrated with part of the system. It is thought that the combination of the performance of the parallel plate waveguide and the structural aspects (e.g. low profile) of the LSLA can be a promising solution. An impression of the LSLA is given in Figure 3.21.

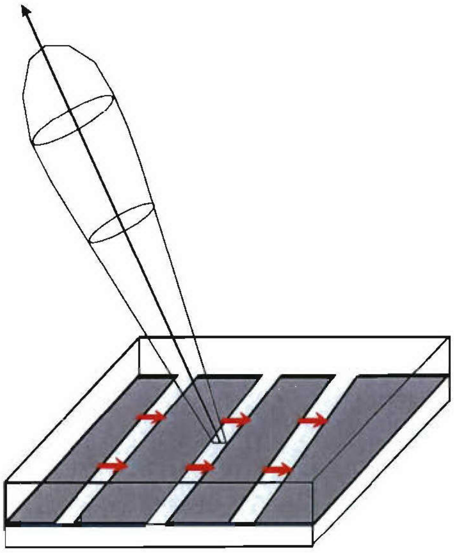


Figure 3.21 Long slots arrayed in one direction, each slot shows an array of integrated feeding points (red arrows). Its characteristics are extremely broadband and allows for hemispherical scanning of the main beam.

It must then however be noted that this array's performance becomes better the larger the array is. For use of such a very wide-band array configuration in a single function system special measures have to be taken to filter out the much larger spectrum of unwanted signals than the relative small band of wanted signals. This kind of array configuration is very suitable for broadband functions like ESM or ECM, however, using only a single polarisation. Single polarisation is surely achievable, moreover, this array has very high polarisation purity with respect to other wide-band radiators. Adding the orthogonal polarisation is not necessarily out of the question. The feeding of the LSLA can be based on microstrip or on coaxial cables. Difficulty in feeding the array could arise due to possible lack of real estate in the direction orthogonal to the slots. A possible solution to this problem is shown in [67]. An EBG structure could be used to suppress eventual guided modes when using microstrip lines for the feeding structure.

3.7 Open-Ended Waveguides

General considerations:
- Thick profile;
- Voluminous;
- Heavy;
- No feeding network;
- Mutual coupling present.

This radiator type belongs to category 3 of section 2 (Figure 2.2a).
The rectangular waveguide is widely used as a transmission line and as an open-ended radiator. The open-ended waveguide radiator has excellent electromagnetic properties and the air-filled standard waveguide version has an impedance level close to that of free space so that there is an intrinsic good match. The open-ended waveguide radiator is very suitable for use, and has extensively been used, in an array environment. The open-ended waveguide used as an array element has been investigated in by several researchers for which reference is made to [59] - [65].

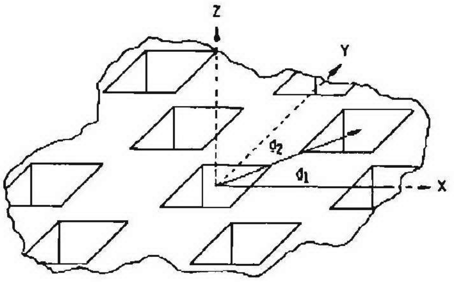


Figure 4.7.1 The open-ended waveguide radiator in an infinite array environment.

The relative bandwidth of the stand alone open-ended waveguide radiator depends on its cross section but in theory may be as wide as 60% for rectangular shaped waveguides whereas for the square of circular shape waveguides a bandwidth of around 20% may be achieved. However, in a practical array environment these bandwidths will not be achieved.
The pattern stability is good and the pattern shape is smooth. Gain may be more than 3 dB (standard waveguide), but depends on aperture shape. Waveguide radiators are suitable for use in a dual polarisation, for that purpose its cross sections needs to be square or circular. For the rectangular waveguide, the cross-polarised component is very low, in case of a square or circular waveguide operating in a dual polarisation scheme, the axial ratio, depends on scan angle and frequency, and may fluctuate considerably.

Waveguide radiating elements have a very rigid construction by nature, both due to their geometrical configuration which is in essence a hollow tube and because of the fact metal is mostly used as a material. For that reason they are resistant to shock and vibration and make the antenna system bulky and heavy on the one side but firm on the other.

In many publications it has been shown that arrays consisting of open-ended waveguide radiators good scanning performance can be accomplished. However, this is always achieved by additional efforts like matching layers, dielectric loading of the elements, irises or a combination of them. For wide-angle scanning array antennas, the magnitude of the reflection changes substantially with scan angle and wave polarization. Conventional matching techniques in the individual element feed lines cannot compensate for these changes. There is a method of wide-angle impedance matching (WAIM) which utilizes a thin, dielectric sheet (ε_r around 9, [61]) spaced in front of the array. It is capable of equalizing the reflection coefficient for E and H polarization at any specified scan angle, or for any angle in the E and H scan planes.

The feeding of the waveguide elements can be various depending on the available space in the array (determined by the array lattice or grid), the application (linear or circular polarisation). Options of feeding are:
- Magnetic loop or H-field coupler (co-axial);
- Electric probe or E-field coupler (co-axial);
- Microstrip line feeding;
- Quasi-Yagi feeder;
- Injection of the field via an opening (slot) in the waveguide wall.

The manufacturing process is straightforward and of moderate difficulty, the higher the frequency the more difficult the manufacturing process. The feeding is more complex to realise, especially when two polarisations are used. Maintaining an array of waveguide radiators is difficult and time consuming and becomes even more complex matching layers are used.

It is possibile to use a material other than metal to produce waveguides; an example is metalised plastics, making the design less heavy and less expensive.
A decrease in the size of the apertures/waveguides, to increase scanning performance, could be achieved by:

- Loading the waveguides with the proper ridges (metal inserts);
- Loading the waveguides with the proper dielectric material;
- Using ultra-short waveguides, so-called compact radiators, and integrating them with the launching structure; matching can be done via tuning stubs [65].

Advantages:

1 Natural steep roll-off frequency behaviour at the lower frequency end of the usable band;
2 Simple element;
3 High power handling;
4 Low loss;
5 Behaviour well known and well described in published reports.

Disadvantages:

1 Wide-angle scanning requires dielectric loading of waveguides to avoid grating lobes. For arrays consisting of dual-polarised radiating elements this dielectric loading is immediately needed. This is forced by their aperture dimension which obstructs the necessary array grid for wide-angle scanning.

4 Considerations

All options of radiators (or radiator configurations like the periodically excited parallel plate waveguide) that could be used in a single function antenna system have been described in the previous chapter. For several of these radiators simulations have been performed to validate their behaviour in an array environment. The main purpose of these simulations has been the validation of the scanning behaviour over a certain frequency band of interest. For other radiators this kind of information could be found in open literature for which the references have been given in the previous chapter.

In the following the necessity of system integration is explained and which of the radiators are suitable for system integration. The following section elaborates on some of the radiators described in chapter 3.

4.1 System Integration

The reader may have noted that the set of radiators described and validated in chapter 4 is quite divers. The ways of feeding these radiators are also very divers, and in fact, even a single radiator may be fed in different ways. Which type of feeding is optimum depends on the radar system requirements and demands. In general it is found that the more relaxed the demands on the radar system, i.e. maximum scanning angle, number of functions to be performed by the system (more functionality meaning mostly larger bandwidth), the less stringent will be the demands on the feeding structure. Nowadays there is a strong tendency to develop more integrated and multilayered (planar) configurations. This tendency is not in favour of the option of co-axial feeding the radiating elements.

Due to technological constraints but also thermal and reliability aspects, it is nowadays not possible to include all the equipment within the array lattice. Because of these constraints and aspects, the equipment parts are physically separated and connected via cables. Therefore, each part has its own (local) mechanical structure. A global antenna structure is needed to assemble and host the complete system consisting of these connected local components. The local structures and the global one account for a large part of the total system mass and, additionally, to the antenna complexity and cost. These disadvantages can be solved by a significant decrease of the size and by integration of the antenna modules. A more compact architecture would result in:

- Lower losses (requires less amplification and, consequently, reduces power consumption);
- Significant reduction of mass.

This explains the tendency mentioned above. Structures, enabling multilayer configurations to integrate the different system parts, are more than any other structure very useful for achieving this goal. The former despite of the fact that in microstrip technology, surface-waves and parallel plate modes (in multilayer designs) may be excited restricting bandwidths and limiting the performance of the complete array system. Several techniques have already been proposed to diminish these effects (one of them are EBG's) and are currently under investigation in institutes throughout the world.

Integration of the different system parts as they have been described above is of course an interesting concept and it may be very well achievable, but still there are the system requirements to be met and that is not always an easy task. Especially planar radiating structures are appropriate for system integration. Often, simple and old proven concepts are still the best solutions to comply with especially radar performance demands for a specific system. Mostly then the demands on the system's physical aspects (weight, volume, geometry) are not met.

4.2 The Radiators

One of the discussed radiators is the periodically fed parallel plate waveguide, see section 3.6. This radiator is not an element that is used to build up an array but already an array configuration by itself, a radiator with scanning capabilities. It may be noted that the elements feeding the parallel plate design "see" each other directly and therefore indeed interact strongly when active. In fact they co-operate via the mutual coupling mechanism, and this is exactly what makes this parallel plate waveguide function properly. The feeding elements can not be taken apart for they will not work decently standing alone. This is in contrast with arrays that are composed of distinct radiators, where it is preferred to have an as low as possible interaction between them. In the case of the parallel plate waveguide, the coupling mechanism is necessary to make this radiator configuration a very broadband one, even for large scanning angles. E.g. in [66] +/- 60 degrees of scanning over a 40% bandwidth have been reported for a slot array antenna. It must be mentioned that only in theory the bandwidth can be much larger. In practice limiting factors such as edge effects and the presence of a backing plane will degrade the performance of the configuration.

The complete contrast between the mechanisms of the parallel plate waveguide and arrays of separate but identical radiators has been mentioned. Mutual coupling in the latter cases will not be as strong as for the parallel plate waveguide configuration. Essentially, when the coupling between the elements is small enough, the modelling of arrays enables a dramatic relaxation of the numerical effort. In that case the standard array theory may be applied. Additionally, little coupling between the elements is very welcome to enable the application of beam forming. The interaction between radiating elements needs to be sufficiently low to prevent additional measures to correct for the corruption of the different radiating element patterns. This involves an extra layer of expensive and complex processing.

5 Conclusions and Recommendations

An investigation has been conducted in order to identify suitable candidates for radiators within the scope of single function phased array antenna systems.
The identified radiators are:

- H-plane sector horn;
- Stacked patch antennas;
- Printed T-dipole antenna;
- Printed Quasi-Yagi antenna;
- Printed tapered slot antenna;
- Periodically excited parallel plate waveguide;
- Open-ended waveguide.

The above mentioned radiators have been chosen for their possibility to be arrayed (e.g. suitable size and shape) and their electromagnetic properties that justify use in an array environment (e.g. sufficient beam width, wide impedance bandwidth, coupling). It must be clarified that not each of the presented radiators can be arrayed in a two dimensional grid. Obviously the H-plane sector horn antenna can not, however, due to its flaring it simulates the effect of arraying (a limited set though) wide beam radiating elements in the H-plane. Disadvantage is the inability to scan in the H-plane and its volume.

For each of the treated radiators special measures need to be undertaken to decrease the mutual coupling between the elements in an array. If these precautions are not taken, the effects may degrade the scanning performance of the different arrays. The various ways of preventing any form of mutual coupling have been described in chapter 3 and range from EBG's to metal fences. For some other configurations like the parallel plate waveguide the mutual coupling can on the contrary be used to increase its bandwidth, the same applies for the tapered slot radiator. Their arrays maintain wide-band even for a large scanning angle.

The printed radiators are almost all of the endfire type and therefore need vertical orientation. In spite of the fact that this makes them bulky, they still might be integrated with part of the system because of the planar technology. The stacked patch radiators however are of the broadside radiation type and are of low profile, also these allow for (partial) system integration. A negative aspect of these radiators is that surface waves may seriously degrade the scanning performance of the array. The tapered slot antenna has good characteristics except for the cross-polarisation which is still a problem. Except for the parallel plate waveguide, arrays based on the other treated radiators enable the use of dual-polarisation. However, this is not the case for the parallel plate waveguide, but has high polarisation purity due to its structure.

There is no possibility to use EBG's in conjunction with the non-printed radiators, although they have been applied to waveguides. Use of EBG's to construct the inner walls made it possible to decrease the waveguide size, unfortunately the same happened to the bandwidth.

The periodically fed parallel plate waveguide has proven to have great potential, in terms of wide angle scanning while maintaining a bandwidth of about 40%. This performance is achieved without much additional techniques to improve it. The disadvantage however, is its volume and the fact that the parallel plates need to have some predefined length in order to ensure proper functioning. The longer the array of feeding points the better the array performance. It is believed that proper functioning is ensured when tiles are arrayed consisting of several feeding points (see section 3.6).

The LSLA (in reference to section 4.2, a planar version of the parallel plate waveguide) could very well be used for a single function system, provided that the bandwidth remains within a certain limit in order to prevent expensive filtering structures. Larger versions of the LSLA could be used to cover the ESM or ECM functions.

The eventual choice of radiator depends on the exact radar application and the demands of system dimensions and costs. This will always involve trade-off(s) between the (not rarely conflicting) system demands. For the application of the concept of system integration an important condition is to use radiators based on planar technology.

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7 Signature

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A Definition of the Radar System Requirements and Functions

The requirements of a contemplated radar system are highlighted in this section and these will subsequently be used to define a list of important evaluation aspects for radiating elements. These aspects enable identification of the most suitable radiators to be used in a single function radar system.

A.1 Radar System

The variety of architectures and technologies used in the current generation of radar systems depends strongly on the mission and the platform that carries the radar system. This diversity is mainly caused by the differences in the requirements imposed on radar systems:

- radiated power and sensitivity;
- volume and weight;
- vibration and shock resistance;
- prime power and cooling;
- electromagnetic and acoustic signatures;
- mean time between failures (MTBF) and mean time to repair (MTTR).

This large diversity in radar systems and technology is one of the reasons that there has been a continuous increase in the share of radar systems in the cost of procuring and maintaining platforms. The development of an open scalable radar architecture that can be sized for various platforms and adapted to meet different mission needs is expected to halt or reverse this trend because the similarities in requirements rather than the differences are emphasised. Radar systems with planar active phased-array antennas are the best candidates for an open scalable architecture because of their inherent scalability in size, performance and functionality. Functional scalability here includes radar functions and also other radio frequency (RF) functions such as electronic support measures (ESM), electronic countermeasures (ECM) and communication.

A.2 Radar Functionality

The antenna is, in general, the major driver of the production cost of an active phased-array radar and should therefore receive a large part of the architecture design effort. There are many different topologies possible for an active phased-array antenna: planar, cylindrical, spherical, conformal, and volumetric arrays. There is a preference for a planar array antenna with respect to scalability.

In general, different RF functions have different polarisations, and bandwidth. Search functions are frequently carried out with horizontal or circular polarisation to reduce sea or rain clutter. Tracking functions use vertical polarisation to reduce multi-path interference, ESM systems often use diagonal polarisation, and satellite communications use circular polarisation. The T/R modules must be capable of transmitting and receiving in different polarisations for active phased array radar to be multi-functional.

There are conflicting requirements between different radar functions with respect to the instantaneous bandwidth of the receiver(s). Search functions generally have modest bandwidth requirements (1 – 10 MHz), whereas tracking and classification functions have medium to high bandwidth requirements (10 – 500 MHz). Defining the antenna array of a multi-function radar system requires at least an idea of the radar application existing at the present time. The following list of naval radar applications was produced after investigating several sources:

Table A.1 RF Functions in the UHF / L / S / C Band.

Application	Frequency band (bandwidth)	Instantaneous bandwidth	Polarisation
UHF SATCOM	260 / 300 MHz		RHCP
UHF communication	225 - 400 MHz		Vertical
ESM	0.5 – 7.5 GHz (15:1)	0.5 – 100 MHz	Diagonal
Volume surveillance	1.2 – 1.4 GHz (15%)	0.5 – 2 MHz	Vertical/ Horizontal/RHCP
IFF	1.03 – 1.09 GHz (6%)	< 2 MHz	Vertical
Link 16 (JTIDS)	960 – 1215 MHz (23%)	3 MHz	Vertical
INMARSAT	1.65 / 1.54 GHz	0.2 MHz	RHCP
Volume surveillance	3 – 3.4 GHz (12.5%)	< 1 MHz	Horizontal
S-Band UDLS	3.1 – 3.5 GHz (12%)	< 1 MHz	Vertical
Helicopter direction	3.05 GHz	1 – 20 MHz	Horizontal
CEC	4.4 – 4.9 GHz (11%)	22 MHz	

Co-operative engagement capability (CEC) will permit groups of ships and aircraft to link their radar systems to provide a composite picture of the battle space, effectively increasing the theatre space. A European version will be available in the future.

Table A.2 RF Functions in the X and Ku Bands.

Application	Frequency band (bandwidth)	Instantaneous bandwidth	Polarisation
Horizon surveillance	8 – 12 GHz (40%)	5 – 10 MHz	Vertical
Weapon tracking	8 – 12 GHz (40%)	5 – 20 MHz	Vertical
Target classification	8 – 12 GHz (40%)	500 – 2000 MHz	Vertical
Target illumination	9.5 – 10.5 GHz (10%)	< 1 MHz	Vertical
Mid-course guidance	9.5 – 10.5 GHz (10%)	< 1 MHz	Vertical
Close-in weapon	8.5 – 9.6 GHz (12%)	1 – 10 MHz	Horizontal / Vertical
Surface surveillance	8.5 – 9.6 GHz (12%)	5 - 20 MHz	Verical
Navigation	9.2 – 9.7 GHz (5%)	20 – 50 MHz	Horizontal
ESM	7.5 – 18 GHz (2.4:1)	0.5 – 100 MHz	Diagonal
ECM	7.5 – 18 GHz (2.4:1)	0.5 – 100 MHz	Diagonal
Common data TX /	15.15 – 15.35 /		LHCP /
Link RX	14.40 – 14.83 GHz		RHCP
SHF SATCOM TX /	7.9 – 8.4 /	< 1 MHz	LHCP /
RX	7.25 – 7.75 GHz		RHCP

In addition:

Application	Frequency band (bandwidth)	Instantaneous bandwidth	Polarisation
Radar surveillance	**8.5 – 9.6 GHz (12%)**	**0.5 – 2 MHz**	**Horizontal/ Circular**
Radar tracking	**8.5 – 9.6 GHz (12%)**	**5 – 500 MHz**	**Vertical**
Jamming	**8 – 18 GHz (1:2.25)**	**< 600 MHz**	**Diagonal**
MilSatCom	**7.9 – 8.4 GHz (6%)**	**< 1 MHz**	**Circular**

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15. ABSTRACT (MAXIMUM 200 WORDS (1044 BYTE))

This report is the result of literature search performed in the "Dual-Band Antennas"-project which is part of the V053 Radar Program. In this study we have focused on the performance of radiating elements suitable for placement in antenna arrays for radar systems that are applied for a single function. Data concerning the performance has been extracted from open literature or if not available via in-house performed computations. Additionally aspects regarding feeding networks and antenna construction have been considered.

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