Antennas in (the) evolution

Citation for published version (APA):

Document status and date:
Published: 01/01/2008

Document Version:
Publisher’s PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:
• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher’s website.
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• The final published version features the final layout of the paper including the volume, issue and page numbers.

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Download date: 18. May. 2019
Antennas in (the) evolution

Where innovation starts
Antennas in (the) evolution

Presented on 14 November 2008
at the Eindhoven University of Technology
Imagine that one day, all the antennas in the world suddenly stop working. In reality, the chance of a simultaneous breakdown of all these antennas is infinitesimal. It could happen if for some reason the electromagnetic laws (on which antennas are based) ceased to apply. But this would mean such catastrophic changes in the world, that the fact that antennas stopped working wouldn’t be our biggest problem. It therefore takes a real effort of imagination to think of such a situation, ignoring the appeal of our rational nature and any scientific argument. This might seem inappropriate in an inaugural lecture, especially in an Engineering department. On the other hand, there is also an opposite point of view, the one of the so-called modern ‘instrumentalism’, which looks at science as something useful, but far away from noble arts like literature and philosophy. To present such a current of thought, I will use the critical description given by Karl Popper in his essay ‘Science and Philosophy’. “There are people who think that science is, in a way, nothing more than something similar to the job of a plumber, although located at higher level. Science is very useful, but it is such that it can represent a menace for the real culture and such that it threatens the imposition of the domain of the ‘quasi-illiterate’ (of the ‘mechanics’, according to Shakespeare). It should be never mentioned together with literature, arts, philosophy. Its discoveries are pure and simple mechanic inventions, its theories are instruments. It cannot reveal, new worlds, hidden behind the surface of the every day life of the world, which is just appearance.”

Like Popper, I don’t agree with this point of view, and if Popper starts from there to derive his theories about science, I would simply like to take the opportunity here to mix some of the different noble disciplines: arts, history, literature and science. So please allow me to go back to my original question. What would the world be like without antennas? The impact would be much, much larger than what you can imagine. In fact, antennas are very often hidden from our eyes; we don’t see them, we don’t feel them, but every day they keep fulfilling their task of making our lives easier, more effective, sometimes enjoyable and very often saving the lives of thousands of people.

No more radio (‘the tribal drum’ as Marshall McLuhan calls it in his essay ‘Understanding Media’), no more television, no more information from space (weather forecasts, monitoring of the environment, space science,
telecommunications...), no more mobile phones, no more radar (on ships, airplanes and cars), no more wireless systems. As a first reaction, someone might consider this a blessing, considering the exaggerated and distorted use that is sometimes made of some of these systems. But with calm and more objective thinking, we should easily agree that the importance of antennas in our world is fundamental. Of course, this is not just due only to antennas, they do not work alone. They are good ‘teammates’, and they work in very close cooperation with waveguide structures, amplifiers, filters etc. etc.

In any case, the function of antennas is to convert electrical signals containing information into electromagnetic waves which are launched into the empty space surrounding us. In a way, they represent an advanced extension of our mouths. The waves propagate in space, bringing with them their important ‘information loads’, and sometimes they travel millions of kilometers before they reach another antenna ready to welcome them, take their message and pass it to whoever was waiting for it. In this way the receiving antennas act as powerful extensions of our ears.

At this point, you may already be asking yourself where I am going to end up, if I am going to continue with this ‘more romantic than scientific’ approach. It's therefore time for a declaration of intent.

In this inaugural lecture, I want to present you with my ‘vision’, my program on advanced antennas. I will try to give an appealing overview of my work program, highlighting in particular those applications on which I will concentrate my research. This clearly requires the use of scientific language and technical terms, but I don't want to limit myself to a purely scientific and technical presentation, for which there are conferences and symposia organized all over the world. I would like to show the relevance and the importance of the research themes that I am proposing for society and for progress. I would like to show how the output of scientific work very often (but unfortunately not always) responds to the needs of human beings, but also influences their evolution. For this, you need more than purely scientific and technical language, so therefore I have decided that this very special occasion is the best opportunity for me to combine the rigorous and rational scientific approach with a bit of art, history and literature.

One of the factors that has had, and still has, a very strong influence on the evolution of the human race is the development of complex and articulate communication. In the beginning, our primitive ancestors used gestures and
simple guttural sounds, which then evolved relatively rapidly into more complex language. Also the elaboration of a writing system, able to provide concrete support for thoughts and words, responded to the human need for communication. But there was still a limitation, due to the fact that interactive communication was only possible over very limited distances. As soon as social life passed the limit of the tribes, as soon as there was the need to explore larger areas and to interact with other groups at larger distances, this pushed human beings to explore other forms of communication: tom-tom, smoke signals, light signals.

This was already an enormous improvement which allowed simple yet effective communication over large distances, overcoming physical barriers. This can also be seen as the start of the process of contraction of distances, which nowadays, thanks to the enormous progress of communication technology, lets larger and larger numbers of people feel part of the same community. Of course, these means were soon no longer adequate for the capacity of the ‘evolving man’, who was able to cover larger and larger distances efficiently, to discover new territories, to maintain efficient control of larger areas. There was a need to provide an efficient and secure communication network. For thousands of years, messengers continuously put their lives in danger to bring important messages to governors and news to citizens. History and literature are full of their heroic deeds: Philippides and his epic ‘Marathon’; the irresistible rides of ‘The Three Musketeers’ with their secret messages, in the famous novel of Alexandre Dumas senior, which so vividly impressed my childhood fantasy; or the Pony Express, the US system of mail delivery with continuous relays on horseback covering about 2900 kilometers in ten days. Once again, the importance of communication for human beings, and the effort that they put into improving it, is indisputable.

Nevertheless, it took thousands of years before Guglielmo Marconi in the late nineteenth century effectively demonstrated the possibility of communicating using radio waves. Although many other researchers had been working on the wireless telegraph idea for many years before him, it was Marconi who made the first real magnificent leap into wireless technology, and who made it practical: transmitting voice and information over enormous distances without a physical connection. Starting from the pioneering experiments of Heinrich Hertz, who was the first to broadcast and receive radio waves in a laboratory, Marconi sent the first ever wireless communication over open sea in 1896: first covering up to 6.4 km on Salisbury Plain, and then reaching nearly 14.5 km across the Bristol Channel. Marconi’s great triumph, however, came a few years later, in 1901, when at St. John’s, Newfoundland, he received signals transmitted across the Atlantic Ocean from Poldu in Cornwall. This achievement created an immense sensation all
over the world, since it demonstrated the possibility of transmitting signals over such distances, despite the opinion of many distinguished scientists that the curvature of the Earth would limit practical communications. Wireless technology has made tremendous progress in the last decades, and it is not difficult to realize how often we make use of it, at home, at work, on holiday, wherever we are in the world. This is a discipline that involves many different aspects, and requires know-how in several fields, of which antennas is one of the most important. Wireless technology is a very strategic field for our University, with the creation of the Wireless Centre (CWT/e) of which I am proud to be part. It is also a very important and strategic field for TNO, constituting, together with electromagnetic fields and antennas, one of the basic pillars of radar, imaging, space and telecommunication systems.

These are actually the most important application areas that I will address in my talk. I will give an overview of trends and challenges in these areas, with particular attention to their implications for antennas.
Antennas for wireless applications come in a very large variety, due to the many different uses, different environments, different platforms and the continuous expansion of the frequency range of operation. Wireless systems require large, medium and small antennas for base stations (from a few meters to a few centimeters), as well as small and very small antennas for the user terminals (down to a few millimeters). These antennas have different requirements, with different technological and design challenges. For example, antennas for base stations are often called smart antennas, since in the most advanced systems they are required to be able to adapt their radiation pattern according to the different environments. For example, to create more beams to follow different users simultaneously, to create nulls in the radiation pattern to reduce interference and disturbing signals, or at least to have the capability to electronically steer the beam to fine-tune the antenna pointing. These antennas do not necessarily need to be ‘miniaturized’, but they might be required to be conformal, to be shaped and adapted to particular supporting structures for reduced visual impact, for aerodynamic reasons or to meet mechanical and thermal requirements. At the same time, wireless systems serve the end-users with their portable devices. In this case, the antennas are totally different and their characteristics are dictated by totally different requirements like: very small dimensions, good efficiency for reduced power consumption, integration with the electronics for ease of manufacturability and cost reduction, and of course structural integration in the ‘portable device’. The frequency range is also very rapidly changing, leading to the development of new antenna concepts and new technological solutions. This trend is mostly dictated by a couple of reasons: the constant increase in transmission capacity required by the new wireless systems, and the crowding of the lower frequency spectrum, where many different bands are allocated to different systems and services.

It is also clear that the use of higher frequencies and therefore smaller wavelengths allows the use of very small antennas, meeting the continuing trend towards miniaturization. Research groups are already looking at the use of the sub-mm wave/THz spectrum for secure communications and short-range wireless systems. By definition, sub-millimeter waves cover the frequency range from 300 GHz to 3 THz. Their propagation in the atmosphere is characterized by a
very high absorption rate. This aspect, which is usually regarded as a drawback, in this case on the contrary makes them suitable for extremely high-capacity short-range secure links. In fact, very directive phased array antennas, which would still have very compact overall dimensions, could provide a point to point signal directionality, and therefore covertness, similar to that of a laser. Furthermore, the very high frequency of operation would allow enormous bandwidths.

I have just mentioned sub-millimeter/THz waves. I will go back to this topic many other times, since I believe that this frequency range represents a new frontier with some of the most challenging developments in the coming years. THz technology is also one of the three main research lines of CWT/e and it will constitute an important part of my research program.
Radar

It is time now to introduce another important research area for antennas, and let me go back again to human evolution.

In their evolution, human beings have developed more and more complex and faster systems of transportation. The domestication of animals like horses and the invention of the wheel, of course, have helped humans to cover larger distances in shorter times, and to reach places which they could never have reached with their own physical strength. The invention of engines meant an incredible leap forward, gradually making human senses (eyesight, hearing) not up to the task of controlling the very rapidly changing environments, and at the same time helping to quickly take essential safety decisions. As we all know, the limitations of human physical performance (we can easily find animals with much better physical performance than ourselves) have been largely compensated by the incredible evolution of the brain, and by the corresponding capacity to develop instruments, tools and in the end technology to provide powerful extensions of our senses.

Radar is an excellent example. The idea of using electromagnetic waves to detect metal objects was first introduced by Christian Hülsmeyer, who in 1904 with his ‘Telemobiloskop’ demonstrated the feasibility of detecting the presence of a ship in dense fog. He gave his first successful demonstration on 17 May on the banks of the Rhine, in Cologne. A few days later, on 9 June, he repeated his experiment in the Port of Rotterdam, after an official invitation from Mr. J.V. Wierdsma, CEO of the Holland America Line. Many other engineers and scientists worked on the further development of Hülsmeyer’s concept, which reached maturity before the Second World War. In particular, the British were the first to develop a real radar system which was effectively used as a defense against aircraft attack and for submarine detection. The use of radar information in 1940 already played an important role in the successful mission of the British fighters during the famous ‘Battle of Britain’, and also for the final successful result of the ‘Battle of the Atlantic’. In this latter case, the final defeat of the ‘U-boats’ was a major achievement, and a major step towards the successful conclusion of the war, allowing an uninterrupted flow of reinforcements across the Atlantic.
In the Netherlands, the initial interest of Mr. Wierdsma was further consolidated in the following years, producing a research and development program that has created the conditions for which this country can be considered as one of the key players in this field.

The basic principle of operation of radar is based on the reflection of electromagnetic waves from objects whose electromagnetic characteristics are different from the surrounding environment. In principle, any solid object embedded in a different medium (typically air), when ‘illuminated’ by an electromagnetic wave, reflects back part of the energy which can then be detected. Radar systems radiate electromagnetic waves in a controlled way (in a well defined angular region and spanning the complete area of interest), and receive the energy reflected by any objects present in the area under consideration. Several types of information can be gained from the reflected signals: distance, velocity and in some cases also the type of object.

Antennas are an essential part of a radar system. Their gain, frequency bandwidth and polarization characteristics have a fundamental impact on the overall system performance. Last but not least, the structural integration of the antenna and the platform is becoming more and an issue in modern systems. Radar is not only used in land platforms, it is also mounted on board ships, aircraft and satellites, and in vehicles. All these platforms require that the antenna is mounted in a way that satisfies specific mechanical, thermal and aerodynamic requirements. Very often, these requirements are not related to the electromagnetic performance of the antenna, and careful trade-offs are necessary.

Two types of antennas are typically used for radar systems: reflector antennas, the most traditional and widely used solutions, and phased array antennas. The latter represent the state-of-the-art, and are the most flexible and advanced antenna systems, but on the other hand they are also much more complex and expensive.

A phased array consists of an array of radiating elements, typically arranged in a regular lattice. In a transmitting array, these elements are fed simultaneously with the same input signal to which a phase delay and, in same cases, an amplitude tapering is applied. Apart from the amplitude tapering, which is applied to properly shape the radiation pattern of the antenna if necessary, the phase delay between the different elements is the real basis of the phased array concept. When all the elements are fed in phase, the electromagnetic fields radiated by
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each element sum up coherently, producing a more directive overall pattern pointing perpendicularly (broadside) to the antenna plane. When a proper phase difference is applied to the array elements, the contributions of the different elements sum-up coherently in a main beam, which is now pointing at a certain angle from broadside. The same principles also apply to a receiving antenna. This represents a very attractive feature for a radar antenna, since it allows the radar to track targets in very rapidly varying environments, and also to change the radiation pattern accordingly, for example to reject jamming (disturbing signals), to avoid interference with other antennas, or to track more targets simultaneously.

Antenna and T/R module technologies for phased arrays have received tremendous attention in the past decades. Nevertheless, this field continuously requires new technological solutions that are able to cope with the requirements of the new generations of advanced radar systems. These requirements are:

- Low cost
- Low mass and low profile
- High efficiency
- Polarization agility and purity
- Large scanning angles
- Wide frequency bandwidths

**Low cost, low mass and low profile technology**

A phased array is a very powerful and versatile antenna, but it is still much more complex and expensive than a reflector antenna. Engineers and scientists are constantly required to look for innovative, low-cost technological solutions, where for example the antennas could be manufactured on typical printed circuit boards, or on multilayer semiconductor technologies used for the development of MMIC components.

This would not only allow considerable cost reduction, permitting the development of the entire front end in the same manufacturing process, but also highly integrated solutions, which are very convenient in terms of efficiency and compactness.

The choice of manufacturing processes very often poses some limitations on the type of materials and on the layouts of the structures that can actually be implemented:

- reduced flexibility in the manufacturing process (difficulty in changing the dimensions of different layers, adding or removing dielectric or metal layers etc. without requiring expensive ad hoc modifications of the process);
the characteristics of the substrates, in particular thickness and dielectric constant (permittivity);
the manufacturability of large panels, or the positioning and interconnection of smaller panels.

Such limitations may prevent the realization of the optimal structure to achieve the best electromagnetic performance.
In particular, the first two factors are related to an important electromagnetic phenomenon: the excitation of surface waves, which have a strong influence on the electromagnetic performance of the antenna and its efficiency. These aspects will be further discussed in the next point.

**High efficiency**
A planar printed antenna on a dielectric substrate with high permittivity can excite surface waves which strongly affect the performance of the antenna itself. Surface waves are electromagnetic waves guided by the overall structure which can trap inside the antenna dielectric substrate part of the energy that should be radiated, therefore reducing the antenna efficiency. Furthermore, when they arrive at the edges of the dielectric support, diffraction effects totally ruin the radiation pattern with the generation of spurious lobes.
In a phased array, surface waves have the additional effect of increasing the coupling between the elements, under certain conditions causing scan blindness effect (unwanted nulls of the radiation pattern). The excitation of surface waves strongly depends on the dimensions of the slab and its permittivity. If a compromise must be found to adapt the antenna to the characteristics of the substrate for the electronic components, novel configurations must therefore be engineered to control or prevent the excitation of such waves. Technologies like Electromagnetic Band Gap (EBG) structures or Frequency Selective Surfaces (FSS) can provide innovative, low-cost solutions. These structures, which can be realized with low-cost planar technology, can be used to produce more suitable substrates for the antennas. An EBG-based substrate, for example, can be designed in such a way that it is characterized by a frequency band in which surface waves are very strongly attenuated. This creates a barrier to the propagation of these waves, and if the antenna is designed to operate in such a band, the problems I just mentioned are solved. I will explain this kind of structure in more detail in a dedicated part of this talk.
At this point, I would rather take the opportunity to stress a very important aspect in electromagnetic/antenna problems: the availability of accurate and efficient analytical models to understand and predict the physical properties of the...
structure under consideration. It is very often impossible or extremely time-consuming to find optimal and innovative solutions with a trial-and-error process, based on the use of general-purpose CAD tools. Such tools are extremely powerful and user-friendly, and can simulate very complex structures, but do not always provide an easy physical interpretation of the electromagnetic behavior, and furthermore often require very long computation times. This means they are not always the best option in an initial iterative design phase, when it is necessary to have a fast response and it is fundamental to understand the most important parameters of the structure and their influence on the electromagnetic performance of the antenna. The development of these models and tools requires a deep knowledge of electromagnetic theory and the mastery of complex mathematical tools.

**Polarization agility and purity, large scanning angles, wide frequency bandwidths**

These are the most important parameters that characterize the performance of an array antenna. The development of array systems which can combine optimal performance for all these parameters simultaneously is a very difficult and challenging task. Often, ad-hoc solutions are proposed to specifically address one of these parameters. Or in general, they are the result of a careful trade-off based on the antenna system requirements. Nevertheless, the development of new array antenna concepts that are able to combine optimal performance with respect to all these different parameters still remains one of the main objectives of most antenna engineers. I would like to conclude this part by mentioning a novel and very promising array concept: the so-called connected array. This is currently the subject of a PhD project at this university, supported by and carried out at TNO. This concept originates from an idea of Prof. Musiaké presented in his original work [1], which dates back to the 1970s. Although based on a purely theoretical concept which cannot be directly implemented in a real system, this idea has been further elaborated in other scientific works [2]-[8], leading to the concept of connected arrays. In a connected array, the radiating elements are electrically connected and not separated as in a traditional array structure. This can for example be realized with a long, periodically fed slot, or with a very long stripline which is again fed at periodic intervals. One of the most advanced demonstrators of connected array developed so far is shown in fig. 1. This demonstrator has been developed at TNO within the PhD project I just referred to. A connected array can provide the best performance in terms of combined bandwidth, polarization purity and scanning capabilities. I will not go into a long and complex discussion to explain their electromagnetic model, but I would just like to highlight again how
the design and optimization of these structures would be impossible without any analytic model. It is not possible to just proceed with a trial-and-error process based on generic electromagnetic CAD tools. We have therefore developed analytical models, which have provided a deep insight into the physics of the structure [9]. Although these models require the introduction of some simplifying assumptions, they are in any case invaluable instruments that provide the guidelines and the necessary know-how for the final optimized design.
Periodic structures

It is now time to introduce a new subject and I would again like to use the concept of evolution. Life originated about 3.5 billion years ago in the form of primordial organisms that were relatively simple and very small. All living things have evolved from these lowly beginnings. At present there are more than two million known species, which are widely diverse in size, shape and way of life. What has produced this incredible result? It has been produced by ‘mistakes,’ or mutations, which occur in the DNA molecule during replication. The result of these mutations is that daughter cells differ from the parents. Newly arisen mutations are more likely to be harmful than beneficial, because their occurrence is independent of any possible consequences. Occasionally, however, a new mutation may increase the organism’s adaptation. The probability of such an event happening is greater when organisms colonize a new territory or when environmental changes confront a population with new challenges. This is also what happens to ideas and theories when they ‘colonize’ new communities. Periodic structures had been widely studied and adopted for many different applications in the microwave community. These applications included microwave tubes, linear accelerators, filters, artificial-dielectric materials, leaky wave antennas, slot arrays, phased-array antennas, frequency-selective surfaces and so on. In the 1990s, the photonics community introduced new concepts and new terminology: photonic band gaps [10]. This terminology and the related structures were suggested mostly by the similarities observed between the stop-band performance of optical periodic structures and solid-state electronic band gaps. This terminology crept into the microwave community where it initially also created some quite strong polemics refuting the novelty of the subjects proposed. It is a matter of fact that in the end, these ideas, these mutations, stimulated new thinking with respect to novel periodic structures, or modifications of existing structures, in order to perform new functions or to improve their performance. This has strengthened the attention in the microwave/antenna community for Frequency Selective Surfaces (FSS) and their applications in combination with antennas, and has produced a variety of novel concepts which can be grouped under the widely accepted terminology of Electromagnetic Band Gap Structures (EBG) and Metamaterials.
In general, these artificial surfaces/substrates are obtained by periodically loading dielectric substrates with metal or dielectric inserts which alter the electromagnetic properties of the overall structure.

Frequency Selective Surfaces represent the first ‘generation’ of structures of this kind, and their main characteristic is to behave like an open filter. In simple words, FSSs can be completely transparent or opaque to electromagnetic waves in a certain frequency band, and exactly the opposite outside this band. Typical uses of FSSs are as dichroics for reflectors, beam splitters and filters in quasi-optical systems, smart radomes to reduce the RCS, and frequency selective screens to prevent problems with Electromagnetic Compatibility (EMC) and Electromagnetic Interference (EMI). The practical example of how an FSS is used to reduce the mono-static RCS of platforms like ships and aircraft can help to illustrate the use of surfaces of this type in combination with antennas.

In this case, the FSS is designed to be transparent in the frequency band of the antennas located inside the ship’s mast or the aircraft’s fuselage, and to be opaque for the out-of-band signals corresponding to detecting radars. By properly shaping the FSS, the out-of-band signal is reflected back, but in a direction different from the incoming signal, where the radar is actually located. This clearly reduces the possibility of detection of the platforms from the radar, while still allowing the correct functioning of the antennas.

If the structures above are examples of widely used FSS applications, they have found new impulses from their combination with components like MEMS and diodes that can render them reconfigurable, and also from their direct integration with antennas. These novel configurations allow new applications like selective screening of rooms, smart radomes for the protection of antenna systems against jamming, and selective ground planes for dual-band antennas.

EBGs represent other very interesting examples of electromagnetic periodic structures. In this case, a dielectric substrate is loaded with an array of metal or dielectric elements in a periodic lattice, which can be realized in three-dimensional (3D) or planar (2D) technology. This periodic loading alters the characteristic of the substrate creating a band gap: a frequency band in which surface waves do not propagate. Surface waves are electromagnetic waves whose field, in normal conditions, is confined and guided by dielectric substrates. It is clear that if a substrate supporting such waves is used to support an antenna, part of the power,
instead of being radiated by the antenna, couples to these surface waves and remains trapped in the substrate. As a consequence:
- the antenna efficiency is much lower;
- the radiation pattern of the antenna presents high secondary lobes due to the scattering of surfaces waves from the edges of the substrate;
- the coupling between the radiating elements of an array is strongly increased by the presence of surface waves, introducing possible scan blindness effect.

A scan blindness effect is an undesired blind spot in the main direction of the antenna due to a strong destructive interaction between the array elements.

Unfortunately, it is not always possible to choose the antenna substrate characteristics in such a way that they do not support surface waves. Very often the integration of the antenna with the electronics and the use of particular multilayer dielectric technologies lead to the use of substrates which could support surface waves. It is therefore necessary to be able to block their propagation, altering the characteristics of the antenna substrate, without spoiling the overall antenna system performance. A very instructive example is given in fig. 2. In these pictures, an EBG structure in purely planar technology, developed at TNO within a project for the European Space Agency, is used in combination with an array antenna consisting of 8 dipole elements [11].

The properties of EBGs can also be used to create a mix of guidance and radiation. For example, by properly removing elements of the periodic lattice it is possible to create a defect in the band gap structure, through which the electromagnetic field can be confined and guided. This can allow the development of integrated structures, in which waveguides, filters, power dividers, antennas etc. can be realized using the same technology.

Another possibility connected to the modification of EBGs is given by the capability of such structures to support electromagnetic leaky waves. These waves are characterized by a very peculiar behavior: they propagate in the dielectric substrate, but at the same time they leak energy by radiation. This means that although they are guided by the substrate, like surface waves, they are not confined and they progressively radiate their energy, therefore fading away along their path. A nice combination of the different effects illustrated so far is the antenna shown in fig. 3. In this case the excitation is surrounded by an EBG sector, which prevents the propagation of surface waves and conveys the energy in the opening of the sector. This opening is filled with a modified EBG structure, which is compatible with the existence of a leaky wave. The leaky wave propagating along this altered EBG structure radiates the energy in free space, acting as an antenna.
figure 2
(a) Linear phased array based on planar circularly symmetric (PCS) electromagnetic band gap (EBG) technology; field distribution inside the dielectric substrate with (b) and without (c) the EBG structure.

figure 3:
(a) Holographic antenna based on planar circularly symmetric (PCS) electromagnetic band gap (EBG) technology; snapshot of the field distribution inside the dielectric substrate with a leaky wave sector (b) and with an entirely closed EBG structure (c).
This last structure allows me to introduce a very intriguing but not yet completely mature concept that is attracting a lot of attention in the scientific community. It is an idea with a tremendous emotional impact on our imagination: invisibility. When is something invisible? When its presence does not impede the view of what is behind it. Extending this idea from optical frequencies to lower frequencies (microwaves, mm and sub-mm waves), the object is invisible when the distribution of the impinging electromagnetic field, on the other side of the obstacle, is the same as it would have been without the obstacle itself. To achieve this, we can imagine the following solution: develop a properly engineered artificial material to cover the object. This material should allow the energy associated with the incident field to be captured, guiding it around the object and then radiating it on the other side of the object, coherently with the non intercepted field, in such a way as to reconstruct the original front wave. Actually, the principle at the base of the antenna mentioned before (combination of surface waves and leaky waves) would allow the implementation of such a concept.

The idea is definitively very intriguing, but it is also necessary very clearly to define its boundary conditions and constraints. At the moment, the main limitation of such a concept is the very limited bandwidth in which the desired effect can be obtained. This means such a concept is not yet applicable, since in most of the applications that can be envisaged, the spectrum of the signal for which the object must be rendered invisible is at least one order of magnitude larger than the available bandwidth. Nevertheless, we all know that history is full of ideas that were first considered to be simply science fiction, but after some years (sometimes more, sometimes less) proved to be feasible and are now part of our everyday life.
At this point, I would like to introduce a completely new topic: THz technology. This is a topic of extreme interest and with tremendous development potential. I have already mentioned what this technology can offer for wireless communication, but this is just one of many applications. In the remaining part of this lecture, I will try to present an overview of the most challenging fields of application such as space science, Earth observation and security (detection of concealed objects and substances). This makes sub-mm wave technology one of the most promising fields of research and development, with an enormous impact on society and extremely interesting market perspectives. A further element which should not be neglected is that the expertise in this field in the Netherlands is remarkable, although scattered among different centers and not yet coordinated. Up to now, the real burst has come mostly from space applications, but the increasingly accurate assessments performed in recent years have shown that there are considerable opportunities in many other fields that will fuel researchers and technologists for many, many years to come.

**Space science**

As a first example of the application field, I will start with space science. One more time, let me go back to the evolution of the human race. We have already discussed the tremendous importance for human evolution of the development of complex and articulate communication. We have also seen the efforts put into the development of means of communicating over larger and larger distances. This, in a way, was also in response to the need for and the attraction of exploring and conquering new territories. In fact, apart from the fascination of the unknown, the discovery and exploration of new ‘worlds’ was and still is also responding to the human need to ensure the availability of new resources for the survival of a constantly increasing population.

When technology allowed the ‘big leap’ into space, the borders of new worlds to be explored became immense. In the last few decades, both manned and unmanned missions have started the exploration of the universe. Who in this room has not at least once seen and been fascinated by the ‘sparkling darkness’ of the images of the first man on the Moon? Increasingly powerful telescopes and other space instruments have been developed in recent decades, and new ones are
continuously being developed to extend our view into space, and our view of the Earth from space. Space science missions study the universe trying to understand our origins; Earth observation instruments help us to monitor our world. Many communications satellites have been placed in orbit to meet our never-ending need for information and communication. Antennas play an important role in all these space missions, and they are the subject of very demanding requirements. It is undisputable that space missions would be completely impossible without antennas.

As an example to illustrate some of the most challenging developments of antennas for space, I will take a new mission by the Japanese Space Agency called SPICA (Space Infrared telescope for Cosmology and Astrophysics). This represents one of the most challenging missions for the exploration of deep space proposed in the framework of the Cosmic Vision (2015-2025) plan. This particular choice is dictated by two main reasons:

• the first reason is that SPICA is supposed to operate in the THz frequency range, and this gives me the possibility to introduce one very important research subject for my professorship: sub-millimeter wave/THz technology;
• the second reason is that a PhD of Eindhoven University of Technology, under my supervision and in close cooperation with the TNO antenna group, is already working on this exciting and challenging subject in cooperation with SRON (Netherlands Institute for Space Research).

A full understanding of how the universe came into existence is only possible by observing the part of the electromagnetic spectrum in which most objects emit detectable radiation. Half of the radiation of a typical galaxy is emitted in the mid- and far-infrared (MIR/FIR) range from dust and gas in the interstellar medium. These kinds of observations in the MIR/FIR are very difficult because of the very low level of the signals, which are also highly attenuated by the atmosphere. This requires the development of instruments and telescopes which must be cooled to cryogenic temperatures (in some cases down to few hundred mK; $1\text{K} = -272 \ ^\circ\text{C}$) to achieve the high sensitivities required, and for most of the spectrum these instruments must be operated in orbit, outside the Earth’s atmosphere.

Clearly this renders such missions very expensive and complex, and progress has therefore been very slow. In the last quarter of a century, only four operational observatories were available, offering limited spatial resolution and sensitivity. It is in this framework that the SPICA mission by the Japanese Space Agency comes into the picture. It will offer an improvement in sensitivity of two orders of magnitude over the most advanced existing instruments, such as Herschel.
(ESA mission), as well as making observations possible over the full MIR/FIR range. This huge increase in sensitivity will allow SPICA in a few seconds to make photometric images that would take Herschel hours, and in an hour to take the full FIR spectrum of an object that would take Herschel several thousand hours. One of the SPICA instruments, the FIR Imaging Spectrometer, will be developed in Europe, under the supervision of ESA, and it will require the development of an ultra-wide band (three bands of one octave each) focal plane imaging system with extremely high sensitivity.

A focal plane imaging system consists of three main parts: the focusing optics, the focal plane imaging array and the back-end. The first part consists of reflectors or lenses whose main purpose is to focus the incoming radiation into the receivers. The focal plane imaging array is a set of antennas arranged in the focal plane of the focusing system. These antennas receive the incoming signal and transfer it to the detectors. Each receiver corresponds to a pixel (resolution cell) of the image. The last part of the system is the back-end, consisting of the signal processing module which produces the final output image.

Mapping a radio-astronomical object is very time-consuming. Due to the very low level of the signal, the system has to pause for a certain time at each pixel of the image, which corresponds to the so-called integration time necessary to improve the signal-to-noise ratio. For a large image consisting of many thousands of pixels, the acquisition of the complete image might require an extremely long time. In terms of performance, a focal plane array offers a tremendous advantage compared with a single-detector system, since it decreases the acquisition time tremendously by using parallel receivers to simultaneously map multiple pixels.

Coming back to the SPICA European Imaging Spectrometer, the main challenges from the antenna point of view are:

- **Extremely high level of integration**: the antenna and the detectors must be tightly integrated, requiring compatible technology and an optimized design to allow perfect matching of these two essential parts of the overall system.
- **The antenna array must be based on innovative concepts** that can achieve the very wide bandwidth requirements, while at the same time being compatible with a technological solution for the realization of very large focal plane arrays of a few thousand elements.
- **Development of ad hoc analysis and design tools**, which should allow accurate design of the focal plane array in all its constituent parts. Such tools should model all the relevant effects that can affect the final performance of the instrument.

Together with a PhD student of this university and the antenna group at TNO which I have the honor and pleasure of coordinating, we have already started
a cooperation with SRON on this topic. SRON is a world-leading research center with state-of-the-art know-how in the development of instruments for space science and Earth observation missions. The main objective of this cooperation is the development of demonstrators of focal plane arrays to prove the readiness of the technology for the SPICA-SAFARI instrument. This mission is considered by SRON to be of strategic importance. Fig. 4 shows the first antenna-detector system designed, manufactured and successfully tested at 670 GHz.

I have already anticipated that there are several other fields in which sub-mm/THz wave technology can play a very important role in the coming years. It is interesting to see once again how all these applications and the corresponding antenna developments respond to problems and issues raised by human progress and evolution. We all know that the first empirical discoveries of our ancestors (fire, metals etc.) up to the most recent scientific ones (engines, nuclear energy, genetic bioengineering, to name just a few), have always been subject to the dichotomy of human nature: good and evil. Each of these discoveries represented a fundamental step in human evolution, extending its potential, its control of nature and its quality of life. At the same time they also provided new ways to satisfy the desire for power and dominance over other human beings, and for wild and uncontrolled abuse of nature. Unfortunately, we all know how common it is in these days to hear news about wars, terrorist attacks, about the destruction of human lives by drugs, and about the tremendous effects on the environment of industrialization and deforestation. Sub-mm imaging systems can provide powerful tools to fight these plagues more efficiently.

**Earth observation**

In the last few decades, all the main space agencies have developed imaging systems at mm and sub-mm wave frequencies for Earth observation, and many new missions with more ambitious objectives are being planned.
For example, Post EPS (EUTEMSAT Polar System) and Post MSG (Meteosat Second Generation) are new missions of the European Space Agency, which is planning the development of the next generations of meteorological satellites. These satellites will help to monitor Earth’s atmosphere and provide real-time images of weather systems. In particular, Post-MSG will provide efficient monitoring of the position of weather fronts and the rapid development of local thunderstorms. GMES (Global Monitoring for Environment and Security) Sentinels is the next flagship initiative for space in Europe. It provides autonomous and independent access to information for policy-makers, particularly in relation to environment and security, such as atmospheric pollution monitoring, flood and fire risk management, forest monitoring, land cover and land use change monitoring, marine and coastal environment monitoring etc. New sub-mm wave payloads are foreseen on board all these satellites.

All these missions are of fundamental importance for the monitoring of our planet. They will help in timely and more accurately predicting the evolution of weather and environment, and in taking important decisions to save thousands of lives, and in the long term the life of our planet. Perhaps we should recall here the historic desire of human beings to predict the future. Think, for example, of the Cumaean Sibyl, one of the most famous priestesses of the Roman and Greek world presiding over the Apollonian oracle at Cumae, a Greek colony located near Naples in Italy. Inspired by Apollo, she wrote her prophecies on leaves, which were then scattered by the wind, making her prophecies ‘sibylline’. This is just one of the many examples of attempts to respond to the desire to know the future, which have accompanied the human race throughout its history. Aren’t weather forecasts and predictions of environmental evolution modern examples of the same desire, but guided by a rational and scientific approach?

Security: detection of concealed objects and substances

Another field of application of sub-mm/THz waves is the detection of concealed objects and substances. For example, small and fast radiometers, based on focal plane arrays, could be used for real-time personal inspection to identify potential terrorists and smugglers carrying concealed guns, explosives or drugs. Terahertz radiation, in fact, has a few remarkable properties that make it suitable for this purpose. Many common materials and living tissues are semi-transparent and have ‘terahertz fingerprints’, while others give rise to much stronger reflections. This allows not only imaging of concealed objects and materials, but also precise identification of some of these substances. This can be achieved by spectroscopic
techniques which identify the typical resonance lines of these materials. Such properties can also be used in non-destructive testing or non-intrusive inspections of postal packages, suspicious suitcases and bags etc. Moreover, the non-ionizing properties of terahertz radiation are inherently safe for screening applications on human beings and animals.

Last but not least, the very small field wavelengths allow the development of very compact systems making use of focal plane arrays with up to a few thousand pixels, which can operate in real-time, allowing covert operation.

Someone might observe that systems for detection of concealed objects already exist, and are used for example at some airports. These systems, which must not be confused with typical metal detectors, mostly work in the lower mm-wave frequency range (90-100 GHz) or with X-rays. The main advantages that sub-mm waves can offer with respect to these solutions are:

- Higher resolution compared with the mm waves, due to the smaller wavelengths of the sub-mm electromagnetic waves.
- Lower health risks than X-rays, due to the very low energy levels.
- Very compact, portable systems, able to operate in real time (thanks to the very small wavelengths, which allow the development of compact focal plane arrays with thousands of pixels).

As also suggested by other colleagues, the extremely well-known and poetic words of the Biblical songs of King Solomon given in the book of Ecclesiastes offer a very poignant conclusion for an overview of sub-mm/THz wave applications:

“To everything there is a season, and a time to every purpose under Heaven: A time to be born, and a time to die; a time to plant, and a time to pluck up that which is planted”, and so on. Indeed the tremendous amount of activities that have been carried out and attention that has arisen in the last years around the sub-mm/THz wave frequency range suggest there are considerable opportunities for the coming years. The increasingly accurate assessments performed indicate that it is time to pluck up the results. Some companies and research institutes are already developing some pioneering and some more mature systems, but this is still a field that offers huge development margins and market opportunities. Furthermore, sub-mm wave/THz imaging is a field of research and development which requires the contribution of many disciplines; not only antennas and electromagnetic periodic structures, for which I will make my modest contribution. This offers the opportunity to involve many other research groups within this university and of course in the rest of the scientific community in the Netherlands, in Europe and in the rest of the world.
Some thoughts on education

Before concluding this inaugural lecture, I would like to spend few words about education: about its role and some of the challenges that must be faced in our society.

I would like to start by citing these famous words of the Divine Poet: Dante Alighieri.

Fatti non foste a viver come bruti, ma per seguir virtute e canoscenza.
Jullie zijn niet geschapen om te leven als beesten, maar om deugd na te streven en om kennis te verwerven.
You were not made to live like brutes, but to follow virtue and knowledge.
[D. Alighieri, La Divina Commedia – Inferno – Canto XXVI – vv. 118-120]

These are the famous words of Ulysses in the Divine Comedy of Dante Alighieri, before leaving on his last journey, encouraging his travel mates to start a new adventure, searching for new worlds and new knowledge. Dante expresses here his high consideration for knowledge, which should have no age and no limits. This is the kind of spirit that should be transmitted to our new generations: the importance of knowledge for ourselves and for the entire world. Man, as the only creature with the capability of discernment and thought, has the responsibility for the future of the world.

Children have to grow up with ideals, which should not be only easy earnings, easy life. This is something for which families, and primary and secondary schools, have a fundamental function. They form the personalities of the young generation. As a university, we have the obligation to raise these issues, we have to guide the students, also the very young ones, to the university and to a right approach to the university; we have to indicate priorities and influence political decisions. We also need to have dreams, ambitious projects. We need to make courageous choices; we need to think with a longer-term perspective and offer it to the students. We have to work for innovation (‘Where innovation starts’ is our motto), offer them arguments that are in line with the state-of-the-art, and of course offer them good and interesting courses and ensure a good transfer of knowledge.
With regard to this last point, it is important to highlight the necessity of a good balance between the transfer of knowledge and research; between the task of transmitting the culture and wisdom of the past, and the pursuit of new knowledge and the achievement of new perspectives. Science privileges the discovery, and science itself has been privileged since the discovery has generated the technology. As a consequence, the more the university has become research-oriented, the more it has privileged research and looked at the 'old' less as an aim in itself, but more as an instrument in the research of the ‘new’. This has resulted in the fact that the transmission of knowledge, among the functions of the university, has received less attention than research. The combination of an explosive growth of specialized knowledge and the tendency of this knowledge to become obsolete has forced the University of our Century to place less importance on the transmission of knowledge. I believe that a proper balance must be found. We want the new students to be as able to master the past as their predecessors. Such a good mix has been found in the Electromagnetic group, with a good balance between state-of-the-art research, applied research and fundamental theory of electromagnetics. My first priority at the university will be the definition and activation of new PhD projects and the tutoring of these students in the fields I have mentioned in this lecture. I will try to offer them the optimal balance between fundamental knowledge, applied research and experimental validation. From this point of view, I believe that the combination of the academic environment and the applied research programs at TNO could represent an optimal melting pot for the formation and maturation of the next generations of researchers and engineers.

I also believe that the full exploitation of the diversity of our modern societies is fundamental for innovation. The participation of all segments of the population, minorities and newcomers can only bring a wider range of perspectives, leading to creative and inventive solutions. In my opinion, from this point of view, the USA is an excellent example. It is sufficient to look at how many famous scientists and how many distinguished professors who made the ‘scientific’ glory of that country originally came from other countries, or belonged to minorities. I am very happy and proud to see how open our university is in accepting international students, researchers and professors from other countries. This is a fantastic opportunity; we have to welcome them, offer them a chance and enrich our knowledge with their knowledge, our culture with their culture.

One last consideration and a recommendation for the present and new generations of students.
I don’t think that only the ‘elected’ people can accept the inexorable burden of moral responsibility with dignity and a clear conscience. This was the idea of the pietistic morality, which mainly reached us through Kant. On the contrary, the ethic of the last century pretends to convince everybody to become worthy of this choice, with full acceptance of responsibilities; responsibilities accepted and proved by the daily engagement. Although this has in itself something heroically utopian, I really share this approach. You are going to be the new generations of engineers, researchers, scientists, managers. You have to be worth of this fantastic opportunity and of the role that you will play in our society.

I would like to conclude with the words of Renée, one of the two main protagonists of the book: ‘L’Elégance du brésson’ by Muriel Barbery (2006, Editions Gallimard, Paris). “What is intelligence for, if not to serve? I am not referring to the false service that proud high state officials exhibit as sign of their virtue: an outward humility that is only vanity and contempt... I must be concerned with the progress of humanity, with the solution of crucial problems for the existence, with the welfare or the elevation of humanity... Shall we devote ourselves to teaching, to the composition of an opera, to research, to culture? It does not matter. In this context, only the intention matters: elevate the thought, contribute to the common interest...”
I have come to the end of this lecture and it is time to express my gratitude and thanks.

I would like to start with my parents. Unfortunately they cannot be present today, but I am sure that their hearts are here with me. Thank you for your unconditional love. Without your education in life, without your loving support in all my important decisions, I would not be here today. Thank you Roberta: for 25 years of life together; for having always shared with me the difficult and the joyful moments; for being able to bear my character, sometimes too ‘arid’ of expressions of love and gratefulness; for always being a point of reference at the difficult moments.

Ho sceso con te milioni di scale dandoti il braccio non già perché con quattr’occhi forse si vede di più. Con te le ho scese perché sapevo che di noi due le sole vere pupille, sebbene tanto offuscate, erano le tue.

[Un milione di scale - Satura, E. Montale, 1971]

Giosuè e Gioele, you are the joy of my life and even though sometimes I am a tough father (as you say), you know very well how great my love for you is and how important you are to me and to your mother. Keep in mind that life is not always easy. Never forget in your life diligence and will, joy and love, freedom and respect and sense of justice.

A special word of thanks to Prof. De Leo and Prof. Rozzi, who introduced me to the fascinating and difficult world of Electromagnetics and guided me in the first years of my scientific career. A very grateful thought to my colleagues at the University of Ancona, with whom I shared long interminable days of work and the pleasure of stimulating and ‘epical’ discussions. Special thanks also to Dr. Guglielmi, who offered me the possibility to come to this country and spend a very fruitful period at the European Space Agency. He has contributed to my scientific maturation and to the fortification of my personality.
I would like to express my profound gratitude to the TNO management who have believed in me and supported me during these years. Thank you for giving me this opportunity.

I would like to thank all my colleagues and all the present and past PhD and MSc students, and in particular a very big thank-you and all my gratitude to my colleagues and friends in the antenna group. Their support and their work have made all the successful results of these years possible.

Last but not least, I would like to express my gratitude to the Executive Board of the university and the board of the department of Electrical Engineering for giving me this opportunity. Many thanks to the new colleagues in the Electromagnetics department, and special thanks, for their trust and support, to the dean of the department Professor Backx, and the chair of the Electromagnetics group, Professor Tijhuis.

Dixi.
Ik heb gezegd.
References

Giampiero Gerini obtained his MSc (Laurea) degree *cum laude* in Electronic Engineering and his PhD in Electromagnetics in 1988 and 1992, respectively, at the University of Ancona, Italy. After his PhD, he had a postdoctoral appointment at the same university, where from 1993 to 1994 he was Assistant Professor of Electromagnetics. From 1994 to 1997, he was Research Fellow at the European Space Research and Technology Centre (ESA/ESTEC), Noordwijk, the Netherlands, in the Radio Frequency System Division. Since 1997, he has been with TNO Defence Security and Safety, The Hague, the Netherlands where he is currently Chief Senior Scientist of the Antenna Unit in the Transceiver and Real-time Signal Processing Department. This position implies the coordination of the overall scientific activities of the Antenna Group, supervision of PhD students and project management of national and international projects with major European research, industrial and governmental partners.

His main research interests are phased array antennas, electromagnetic bandgap structures, frequency selective surfaces and integrated antennas at microwave, millimeter and sub-millimeter wave frequencies. The main fields of application are radar, space and telecommunication systems.
Antennas in (the) evolution

Where innovation starts