Planar Circularly Symmetric Electromagnetic Band-Gap Antennas for Low Cost High Performance Integrated Antennas

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***Abstract*— The use of Planar Circularly Symmetric (PCS) Electromagnetic Band-Gap (EBG) structures for optimizing the performances of single antenna elements and arrays is been discussed. The key advantage of using this sort of super structures is that they are planar and thus very cheap to manufacture with respect to alternative EBG structures based on vertical pins. In this contribution a review of the design principles and of the antennas based on PCS EBG which have been developed at TNO will be presented. Also a review of the applications that effectively used the benefit associated with them will be discussed. In conclusions, while EBG technology has been promising marvels for phased array applications for quite some time, its PCS implementation eventually turned out to be a one of it most successful examples. In fact it delivered low cost, broad band and efficient integrated antennas which could not have been realized otherwise.**

I. INTRODUCTION

ELECTROMAGNETIC band-gap (EBG's) materials [1], have been proposed for solving a wide variety of E.M. problems [2]- [4]. However, before EBG technology will be successfully adopted by industry for Radar or terminal antennas, an important step should be taken. Clear and objective (i.e. quantitative) evidence of the advantages of EBG technology is required. In a series of recent works [5] [6] [7] the use of Planar Circularly Symmetric (PCS) Electromagnetic Band-Gap (EBG) structures for optimizing the performances of single antenna elements and arrays has been discussed. The key advantage of using this sort of super structures is that they are planar and thus very cheap to manufacture with respect to alternative EBG structures based on vertical pins [2] [4]. Using PCS-EBG's a completely planar antenna with 20% of bandwidth which does not suffer from surface wave effects was presented in [5]. Also completely planar 8 element antenna array also 15% of bandwidth which also not suffering from surface wave effects was presented in [6]. In this contribution a review of the design principles and of the antennas based on PCS EBG which have been developed at TNO will be presented. Also a review of the applications that effectively used the benefit associated with them will be discussed. The PCS EBG's have in fact been used in a number of Radar systems developed at TNO ranging from UVA based S.A.R. to FMCW security radars and to maritime surveillance. Also they have been used in 60 GHz wireless communications transceivers. In conclusions EBG technology which has been promising marvels for phased array applications for quite some time. We believe that its PCS implementation eventually turned out to be a one of it most successful examples as at least it delivered low cost, broad band and efficient integrated antennas which could not have been realized otherwise.

II. DESIGN PRINCIPLES

A. 2D EBG's

The 2D EBG structure that will be considered to start the present discussion is the one in Fig. 1. It includes a ground plane with a dielectric layer on top of it. The existence of a periodic metallic loading on top of it is considered possible. Moreover the slot on the bottom ground plane is for the moment considered only functional to indicating the polarization which will be assumed for this completely 2D problem. Only electric currents along x on the EBG can be considered to characterize the problem. The dispersion equation pertinent to these structures were solved in a quasi analytical way in [5] which lead to the availability of a simple code able to characterize the dispersion properties of these structures. In fact in absence of the periodic loading a TM wave can always propagate on such slab structures and the propagation constant of such surface waves can be found almost analytically. In the presence of a loading these surface waves are perturbed, heavily or not depending on how close to resonances are all the dipoles which load the structure. When the perturbation is so strong that it leads to only attenuating waves, the structure is a band gap for that frequency and that first TM wave. The structures were also characterized via the attenuation constant which turned out eventually to be the single most important factor in the design. This exercise, even if performed in an original way, was not truly original as other authors had characterized similar structures before, [8]. Figure 2 shows the dispersion diagram of the EBG structure used in the demonstrators described in following sections.

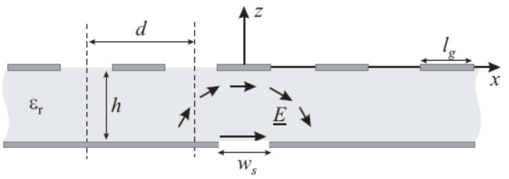

Fig. 1 Canonical structure representing the 2D starting problem used to characterize PCS EBG's

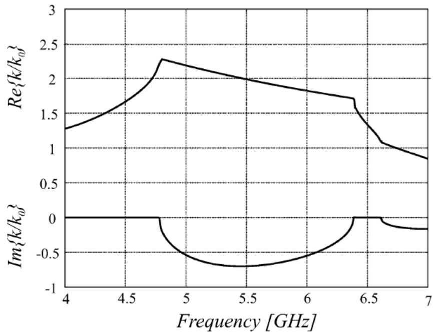

Fig. 2 Dispersion diagram for the TM surface wave (d = 13:7 mm, l = 6:6 mm).

B. PCS-EBG'S: TM surface wave launchers

The first important steps performed [5] was establishing the equivalence between the waves propagating in structures such as the ones in Fig.1 and the ones in more realistic 3D structures as in Fig. 3

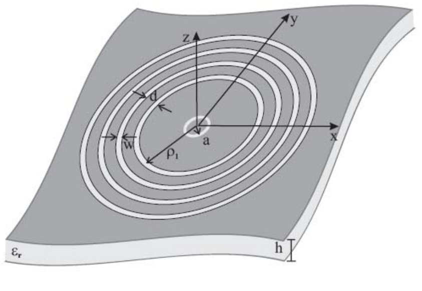

Fig. 3 Planar Circularly Symmetric EBgs, with ideal symmetric source.

From the analysis of the comparison between the results pertinent to structures as the ones in Fig. 1 and the ones of Fig. 3 it was possible to establish equivalence between arbitrary frequencies inside or outside the band-gaps. Then one can deduce that the presence of a frequency band-gap from the TM_0- propagation in a 2D-EBG case implies its existence also in a PCS-EBG. The mayor differences are in the spreadings:

1) A plane wave behavior in the 2D equivalent structure corresponds to a cylindrical spreading in the CS structure.
2) A cylindrical spreading in the 2D equivalent structure implies a $1/\ \psi$spreadingψin the CS structure

C. Single Antennas with surrounding EBG's

In the previous structure of Fig.3 a symmetric TM source was assumed, that generated only a pure TM field with the electric field entirely polarized along ρ. Continuous rings were used to stop the surface wave propagation. When the source is not symmetric, it generates electric field components in both, ρ and φ, directions. If one was simply to use the rings that were previously introduced they would support azimuth electric currents that can lead to strong resonances. Such strong resonances will then be responsible for a significant alteration of the input impedance and thus a bandwidth reduction.

However the electric field associated to the TM surface waves presents, for large values of ρ, an electric field with only the ρ component. Thus a simple modification of the PCS-EBG configurations that resorts to dipoles oriented in the radial direction around the source can be applied. The radial dipoles will only act on the ρ component of the electric currents (or of the electric fields), so will not introduce additional resonances. Except for this the dipoles behaved almost exactly as the rings.

In Fig. 4 the geometrical parameters of this new configuration are shown. The radial position $\rho_i = \rho_1 + (i - 1)d$ and length l_g can be designed using the same equivalent 2D-EBG model as before. Then, there are two additional parameters the width of the dipoles w_g and the angle at which the dipoles are placed α (it defines the number of dipoles per ring). Simulations have shown that the influence of w_g is small, while the angle α has to be chosen so that the $TM0$ mode still experiences a continuous surface. In terms of array theory this implies that each wave front, that has normal incidence, must encounter elements that are in the at λ_0: $D_{max} \leq \lambda_{eq}/2 \leq \pi/k$ where k was the propagation constant of the mode. Approximately $D_{max}<d$

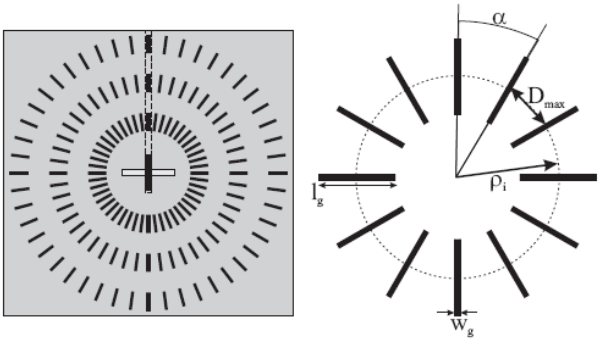

Fig. 4 Planar Circularly Symmetric EBgs, with an antenna source at the center. Indicated are also the geometrical parameters that characterize the structure.

Another important factor in the design of antennas surrounded by EBGs is the impedance bandwidth. In [7] a simplified 2D model was derived to characterize the interaction between the antenna and the EBG as a function of the distance between the antenna and the EBG, It was found that the optimal radiation bandwidth is achieved when the inner radius of the equivalent EBG cavity is approximately half of the first surface wave wavelength . In this situation the wave reflected from the EBG cancels out the outgoing waves emanated by the source. Any other configuration reduces the BW.

III. ANTENNA DEMONSTRATORS

A. *Single Antenna*

The antenna considered in this section consists of two dielectric slabs with the same dielectric constant and different heights divided by a ground plane. A slot etched in the ground plane is coupled to an orthogonal dipole located on the top of the upper dielectric slab. Finally, the structure is excited via a micro-strip. In order to quantify the effect of the EBG structure on the performances of this antenna, a panel composed of six printed antennas has been built (Fig. 5). Two of these antennas are surrounded by a PCS-EBG consisting of two or three rings. The other four antennas are simple printed antennas. The antennas are printed on dielectric material with εr = 9.8 commercially available from Rogers.

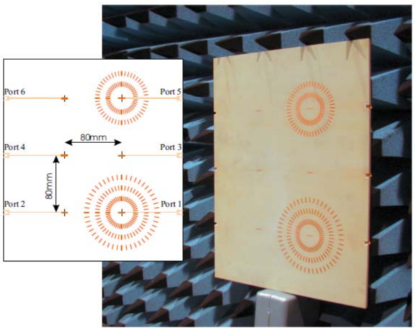

Fig. 5 Panel with six single antennas with and without EBG.

Figure 6a shows the s-parameters of the antennas without EBG. The measurements are compared with the simulations done using Ansoft Designer. The maxim coupling is in the E plane and it is around -17dB. Figure 6b shows the s-parameters related to the antenna with the two rings EBG surrounding it. The impedance bandwidth is improved to 20% thanks to the cavity effect. Most importantly, there is a significant reduction of the coupling between the two antennas. Finally, the results pertinent to the three rings show a further reduction on the coupling thanks to a higher attenuation of the surface wave. The coupling is then limited by the space wave contribution.

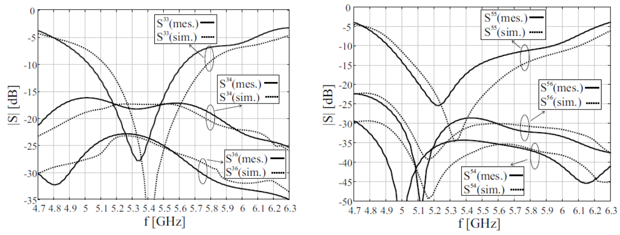

Fig. 6 S-parameters pertinent to (a) simple antennas and (b) 2 rings EBG antenna

The panel has been cut in portions of the same dimension in order to perform the radiation pattern measurements of the three different antenna configurations (no EBG, two rings EBG and three rings EBG). Figure 7 shows the co-polar radiation patterns in the H- and E-planes measured at the central frequency (f = 5.4 GHz) for all three antennas considered. We can observe that the impact of surface wave diffraction on the single antenna pattern is significant, with a first deep null well inside the 3 dB radiation pattern zone.

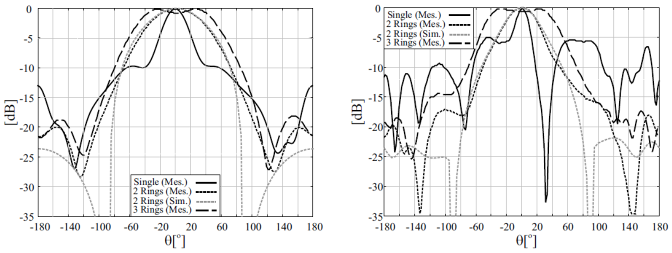

Fig. 7 Measured H-Plane (a) and E-Plane (b) Radiation Patterns for the single antenna, the PCS-EBG antenna with two rings and three rings. In both figures the patterns calculated with Ansoft Designer are also provided for the antenna surrounded by 2 rings.

The EBG prototype has been simulated with MWS CST as well. Figure 8 shows the total electric field launched, inside the dielectric substrate, by a single antenna (a) and by the 2 ring EBG antenna (b). One can clearly observe that the field is concentrated inside the cavity created by the EBG and that the surface wave is strongly reduced outside.

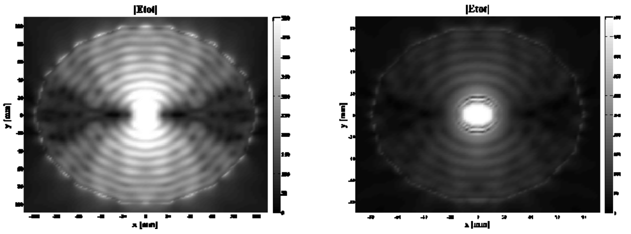

Fig. 8 View of the total electric field inside the substrate launched by an aperture coupled dipole (a) and surrounded by 2 rings of PCS-EBG (b).

B. *Array Antenna*

The PCS-EBG concept is well suited for 1-D scanning arrays. The main design principle is to use linearly polarized antenna elements arrayed in the H-plane. From Fig. 8a we can see that a slot coupled dipole launches TM surface waves predominantly in the E-plane cut of the slab with a cosϕ angular distribution of the field intensity. For this reason, one could use PCS-EBGs to reduce the TM waves only in a specific angular sector, where the waves are predominantly launched. An array prototype, Fig.9, has been built following these guidelines. $\phi \in [-38^{o},38^{o}] \cup [-142^{o},142^{o}]$ is the angular sector where the surface propagation is blocked in each array element. Integrating the power distribution over this sector, one obtains that 73% of the surface wave power is blocked. The angular sector concept allows closer spacing of the array elements, with respect to the cases when full rings were employed, leading to better scanning performance in the H-plane.

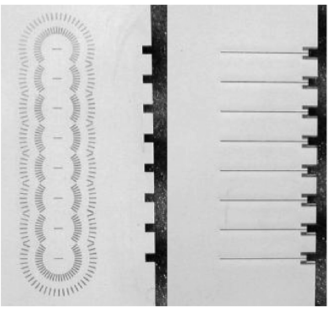

Fig. 9 1-D scanning array composed of 8 elements with PCS-EBGs (front and back view).

The active s-parameters of the array prototype have been measured showing a 15% bandwidth [6]. The active radiation patterns have been also measured and are shown in Fig. 10. The patterns are normalized to their maximum value and the comparison with the results predicted by CST simulations shows good agreement. Fig. 10a and b show the H-plane for broadside and 40^o scanning, respectively. The beam is clean and the only noticeable aspect is that the cross polarization patterns are larger when scanning. The E-plane radiation patterns are shown in Fig. 10c for the case of broadside radiation. In this case, the patterns are not normalized and the values shown correspond to the measured and calculated directivities. It can be seen that simulations performed via CST and measurements are fairly similar with differences that are within calculation and measurement accuracy. The actual values in both cases oscillate around the values predicted for an infinite substrate (Ansoft Designer simulations). This explicitly shows that the effect of the residual surface wave diffraction is still somehow present in the E-plane. This is congruent with the estimated array surface wave efficiency of 85%.

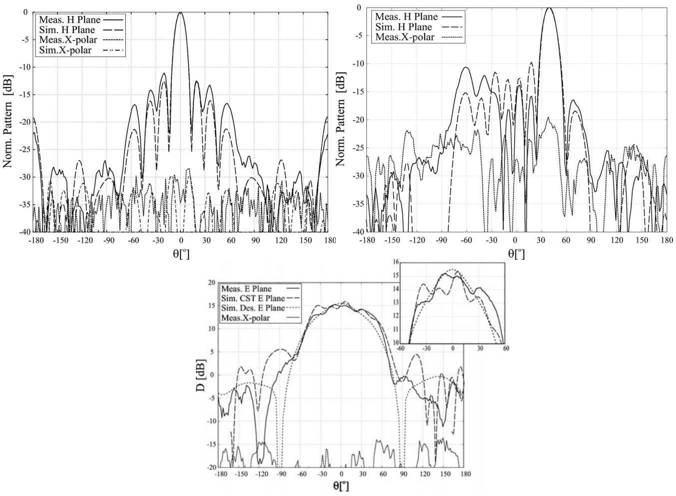

Fig. 10 Measured radiation patterns of the 1-D scanning array: (a)H-plane at broadside, (b) H-plane at 40^o and (c) E-plane.

This efficiency is in line with the one of the single antenna. The surface waves generated by a single antenna present a cylindrical spreading in all radial directions, and therefore the associated power is dispersed over a wide angular sector. In the present array configuration, the residual surface waves (not completely attenuated by the EBG) have a stronger impact on the radiation pattern and can be more easily identified. In fact, in the present array case the surface wave power is not spread over a large angular sector, but focused in certain preferential planes, because the surface waves form a unique coherent wave front in the direction dictated by the array phasing. We can observe this in Fig. 11a, that shows the electric field inside the substrate launched by the array without EBGs. Figure 11b shows the same field but when the array is surrounded by the EBG. We can see the strong attenuation of the surface wave as well as the residual surface wave edge effects.

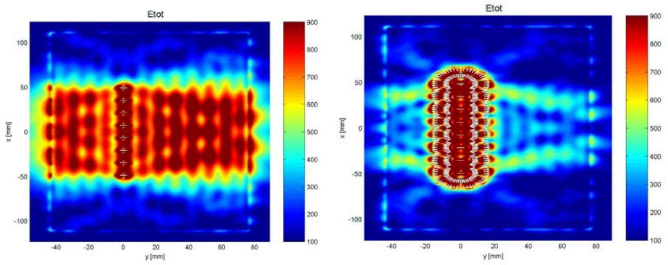

Fig. 11 View of the total electric field inside the slab with no EBGs (a) and with EBGs (b).

IV. APPLICATIONS

The PCS-EBG based antennas discussed in the last section have been used in a number of real system that the system group at TNO Defense were asked to develop and required wide band planar antenna technology.

A. *Mini SAR*

An extension to 16 elements of the PCS-EBG array discussed in the last section has been used in the Front End of the Mini-SAR: the synthetic Aperture radar developed entirely by TNO for the Dutch Ministry of Defense to be mounted on an unmanned drone. The array operates in X band, it is requested to frequency hop over at least 15% BW and is linearly polarized. Requirements on the power efficiency are also tight given some minimal requirements on the signal to noise ratios and a maximum power consumption possible. e mentioned in this section.

B. *EMERALD*

Another important radar developed by TNO and presently being tested is the so called EMERALD. It uses almost the same X band frequencies. It is based on an FMCW front end, and accordingly uses two separate antenna arrays in order to meet very stringent isolation requirements between the Transmit and Receive channels.

V. CONCLUSIONS

In this paper the short story of a four years long development activity has been described. The PCS-EBG theoretical investigations allowed us to find a way to realize printed planar antennas characterize by wide bandwidths but completely planar and efficient at the same time. Once these antennas were available they have been exploited by TNO isn a number of application driven system which we have only begun to describe. Overall this is certainly a success Research AND Development story.

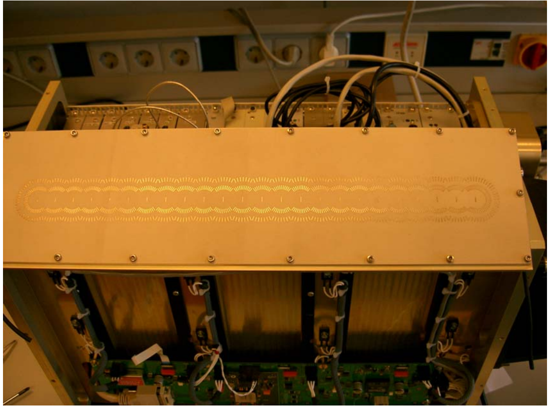

Fig. 11 A photograph of the Mini-SAR prototype with the T/R modules (hidden by the array) and the control units.

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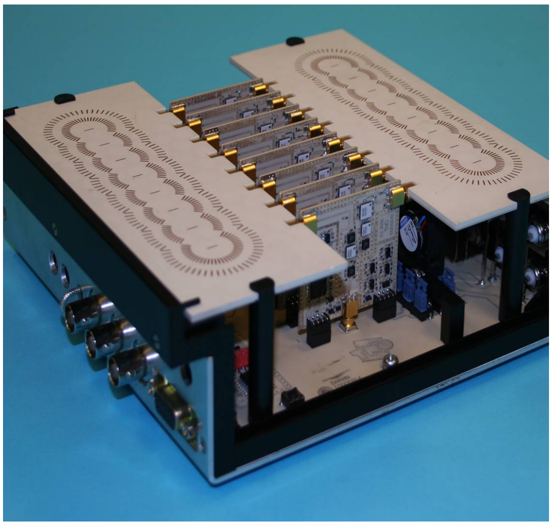

Fig. 12 A photograph of the EMERALD system developed for security and maritime applications.