Bandwidth, Efficiency and Directivity Enhancement of Printed Antenna Performance Using Planar Circularly Symmetric EBGs

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Abstract— **Planar Circularly Symmetric (PCS) Electromagnetic Band-Gap (EBG) substrates have been recently proposed to suppress the surface waves in printed technology [1] [2]. The major advantage of the PCS-EBGs with respect to structures based on vertical pins [3] [4] is the fabrication simplicity since the dielectric slabs do not need to be perforated. With respect to other planar type of EBG [5], an advantage is that the surface waves launched by a central source are reduced equally in all radial directions. The motivation of this contribution is to design and measure a prototype which demonstrates the suppression of surface waves by a PCS-EBG of a single antenna printed on a dielectric substrate. Thanks to the presence of the PCS-EBG around the antenna, we obtain an enhancement of the bandwidth, efficiency and directivity performances. The study will present some design considerations for the PCS-EBG itself, and then will proceed with the manufactured and measured antennas. The results explicitly show the advantages in terms of bandwidth and radiation pattern of the proposed EBG substrate. A bandwidth of 20% is achieved without significant surface wave losses.**

Fig. 1.   Panel with six antennas located in a square grid of 80mm.

I. INTRODUCTION

Electromagnetic band-gap (EBGs) materials [6] are being proposed for solving a wide variety of E.M. problems [3]–[5]. In this paper a procedure to design artificial substrates that impede surface wave propagation over wide bands, and are suited to host antennas with bandwidths up to 20%, is presented. The planar structures that we consider are circularly symmetric and radially periodic and are aimed to the suppression of the TM_0 mode of the grounded slab. The key characteristics of PCS-EBGs are the following: they are simple to manufacture since they do not present vertical via holes or pins, they do present the same band-gap properties for different directions of propagation, and, finally, PCS-EBGs can be designed starting from a 2D equivalent geometry with a 1D periodicity. The 2D geometry yields a very good first order estimation of the overall performances of the relevant 3D geometry, while reducing the numerical effort.

In order to quantify the improvement of the PCS-EBG on the performances of a central antenna, a panel composed of six printed antennas has been built (Fig. 7). Four antennas are simple printed antennas whose geometry is explained in section II. The other two antennas are surrounded by a PCS-EBG consisting of two or three rings. The geometry and design issues of a PCS-EBG are explained in section III. The improved performances can be seen in terms of increase of bandwidth, reduction of the mutual coupling between the antennas, cleaner radia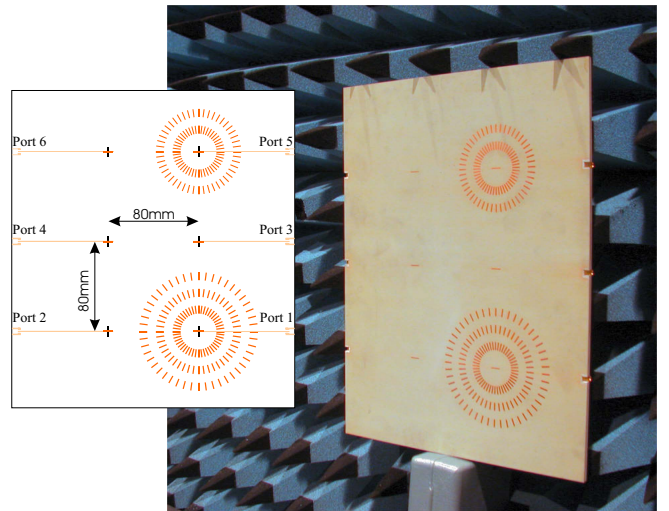tion pattern due to less edge effects and improvement of the gain. The measures of the S-parameters are shown in section IV, and finally the radiation patters and gain are shown in section V.

II. MICRO-STRIP EXCITED, SLOT COUPLED DIPOLE

The central antenna, in absence of the EBG, is shown in Fig. 2. It consists of two dielectric slabs with the same dielectric constant ϵ_r and different heights h and h_m divided by a ground plane. There is a slot etched in the ground plane of dimensions l_s and w_s. The slot is coupled to a orthogonal dipole (l_d and w_d) located on the top of the upper dielectric slab h. Finally, the structure is excited via a micro-strip whose extension beyond the slot crossing is l_{stub} while its width is w_m. The micro-strip is printed on the other side of the lower dielectric slab h_m.

Printed antennas usually use low dielectric constants so that there is no significant excitation of surface waves. However, when using slot coupled antennas, this comes at the cost of a low front to back ratio which often implies the presence of a backing reflector. Such backing reflector will eventually allow the propagation of parallel plate waveguide modes, which will have to be eliminated somehow, for instance by using EBGs or cavity backing. The key advantages of antennas printed on moderately high dielectric constant slabs ($\epsilon_r = 10$) would be
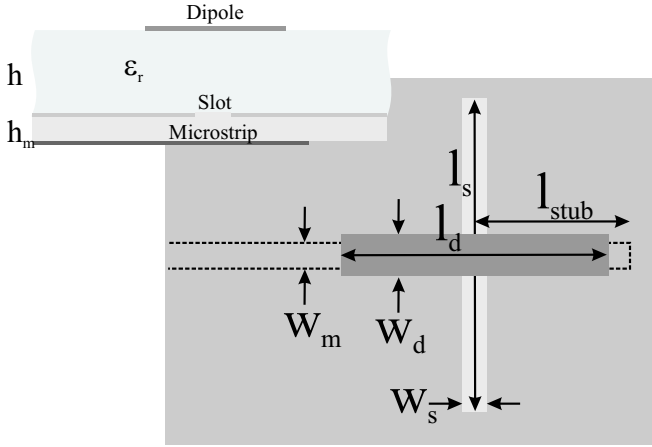
Fig. 2. Side and top view of the printed antenna: Slot (l_s,w_s) coupled to a dipole (l_d,w_d) and excited via micro-strip (l_{stub},w_m).
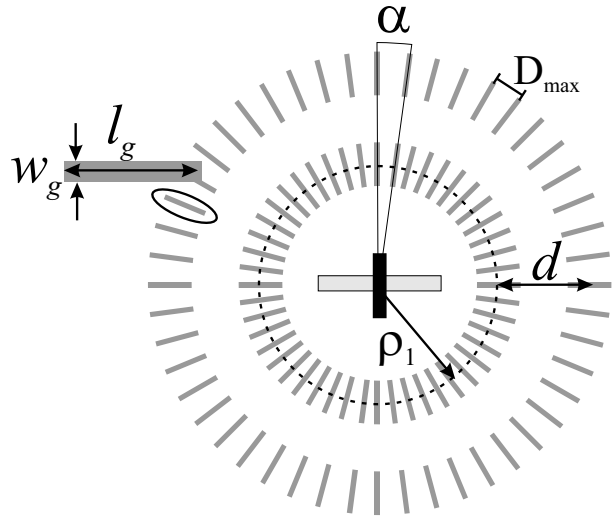

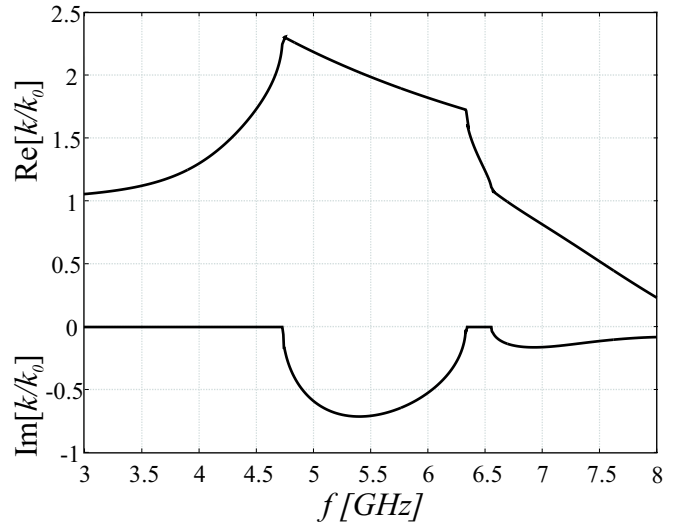Fig. 3. Geometrical parameters of a PCS-EBG.

Fig. 4. Dispersion diagram for a grounded slab with parameters $\epsilon_r = 10$ and $h = 3.81mm$ loaded by a strip grating of $d = 13.7mm$ and $l_g = 6.6mm$

the simplification of the feeding network since the front to back ratio would result higher. In [7] was demonstrated that the impedance bandwidth of a printed antenna is maximum for slab of thickness close to the radiation peak ($h \approx \lambda_d/4$), which corresponds to the excitation of the second slab mode, i.e. TE_1. Even if the substrate we considered in this paper has such a thickness that only the TM_0 mode is in propagation ($h \approx 0.22\lambda_d/4$), the surface wave results extremely strong excited. In case of moderately high dielectric constant slabs ($\epsilon_r = 10$), more than 70% of the total power is launched into the first TM surface wave [8]. As consequence these antennas are not suitable unless an ad hoc procedure to block surface waves is introduced.

III. DESIGN OF THE PCS-EBG

The PCS-EBG structure, shown in Fig. 3, is arranged in a circularly symmetric form to provide an effective control of the surface waves generated by a central antenna in all radial directions. The radial positions and lengths of the dipoles, (l_g, d), are designed using a two dimensional problem in order to obtain a band-gap of the TM_0 mode in the frequency band of interest. The dispersion diagrams of 2D-EBG were calculated in [9]. The procedure included the set up of an integral equation enforcing the vanishing of the electric field (EFIE) on the metallic loadings. In Fig. 4 the real and imaginary parts of the normalized solutions, k/k_0, of the dispersion equations pertinent to a grounded dielectric slab ($\epsilon_r = 10$, $h = 3.81mm$) loaded by a strip grating ($l_g = 6.6mm$, $d = 13.7mm$) are shown.

In [1], PCS-EBGs were used to suppress the surface waves launched by a symmetric TM source to improve the efficiency of such antennas. A symmetric TM source generates 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 TM symmetric, it generates electric field components in both, ρ and ϕ, directions. If one was simply to use the continuous rings, they would support azimuthal 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 it can be demonstrated that the electric field associated to the TM surface waves, for large

values of ρ, has an electric field with no ϕ 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.

The influence of the width of the dipoles w_g is small. Instead, the angle at which the dipoles are placed α (it defines the number of dipoles per ring), has to be chosen so that the TM_0 mode still experiences a continuous surface (like continuous rings). In terms of array theory this implies that each wave front, that has normal incidence, must encounter elements that are sampled in ϕ, at least, at the Nyquist frequency: $D_{max} \leq \frac{\lambda_{TM0}}{2} \leq \frac{\pi}{k_{TM0}}$ where k_{TM0} is the propagation constant of the TM_0 mode of the grounded slab. The parameter ρ_1, instead, is selected to be half of the surface wave wavelength, λ_{TM0}:
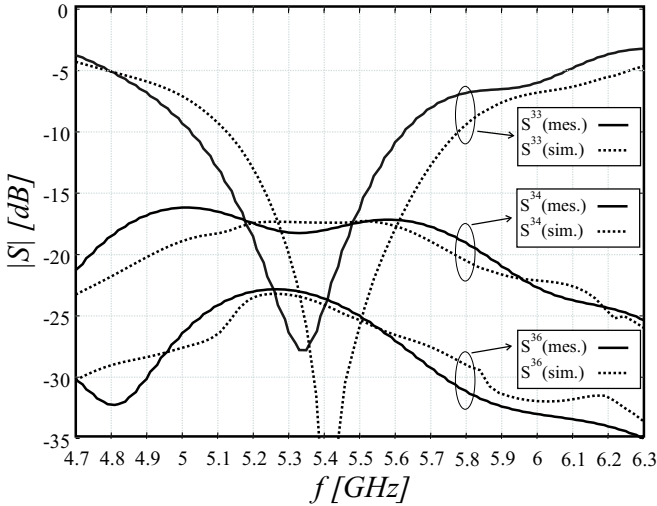
$$\rho_1 = \frac{\lambda_{TM0}}{2} \qquad (1)$$
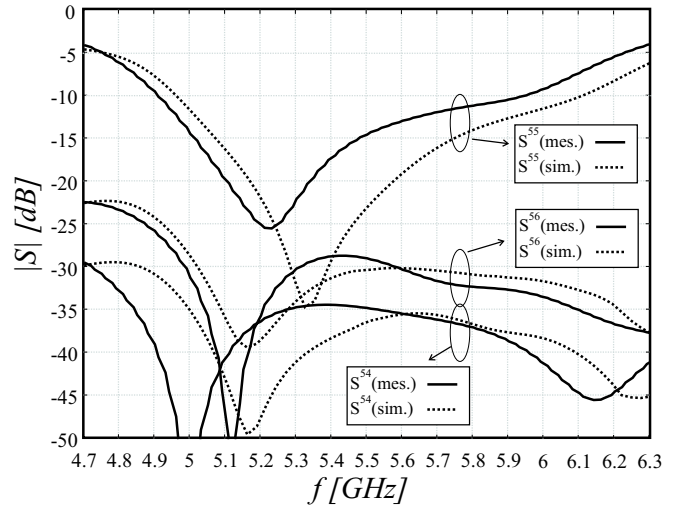
Fig. 5. S-parameters pertinent to the antennas without EBG

Fig. 6. S-parameters pertinent to to the antenna surrounded by 2 rings of dipoles

in order to enhance the radiation bandwidth. In this condition, the surface waves launched by the central source are cancelled by the ones reflected from the EBG. Thus only the spectral components of the fields contributing to radiation are significant in the source. This aspect will be further investigated.

IV. S-PARAMETERS

Fig. 5 shows the S-parameters pertinent to the antennas without the PCS-EBG around them. The measurements are compared with the simulations done using Ansoft Designer. One can first note that the single element impedance bandwidth ($S_{33} < -10dB$) is in the order of 12%. This bandwidth is not useful because this antenna has a very poor efficiency of around 40% due to the strong excitation of surface waves. The S_{34}, case in which the antennas are situated at a distance of 80mm ($1.45\lambda_0$ at the central frequency) in the maximum coupling direction, is around -17dB. The second parameter S_{36} is around -23dB and corresponds to case where the antennas are placed at 45° one to the other. For both these configurations the coupling is essentially due to the TM_0 surface wave.

Fig. 6 shows the S-Parameters related to the antenna with the two rings EBG surrounding it. The S_{55} parameter of the antenna surrounded by the EBG is improved, thanks to the appropriate selection of ρ_1, so that the impedance bandwidth is about 20%. Most important, there is also a significant reduction of the coupling between the two antennas. Both the S_{54} and S_{56} parameters are reduced in around 10dBs arriving to coupling levels dominated by the space wave. These results show that as far as impedance bandwidth is concerned PCS-EBG may be tuned to achieve 20% bandwidth without surface wave excitation.

Finally, the results pertinent to the EBG based on three rings are not discussed here. It should be mentioned that the third ring does not significantly improve the isolation between the antennas, because thanks to the attenuation in the band-gap (imaginary part of k in the dispersion diagram, fig. 4) two rings are sufficient to suppress the surface wave.

V. RADIATION PATTERNS

In order to perform the measurements and obtain a fair comparison between the performances of the different antenna
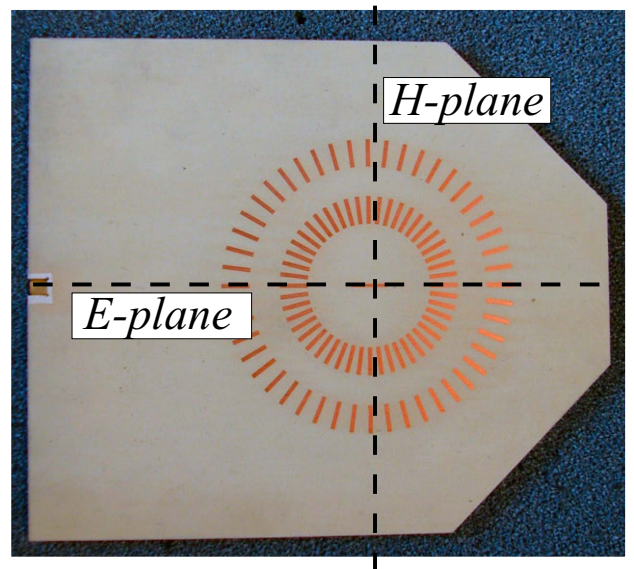

Fig. 7. Panel portion containing the antenna surrounded by two rings

configurations (no EBG and two rings EBG), the panel has been cut in portions of exactly the same dimension. A photograph of one of these panels is shown in Fig. 7. Also the E-and H-plane cuts are shown in the same figure. The measurements were then performed in the cylindrical near field scanning facility at TNO.

Fig. 8 and Fig. 9 show the co-polar normalized radiation patterns in the H-plane and E-plane mesured at the central frequency (f=5.4GHz) for the two antennas considered. Observing the H-plane first, Fig. 8, one can notice a very significant difference between the 3 dB angle obtained with and without EBGs. Especially in absence of EBGs, the surface wave diffraction is expected to heavily affect the actual radiation patterns. Fig. 9 shows the measured radiation patterns pertinent to the E-plane, which is the plane where the surface waves is strongest excited. In this case the patterns are in general not symmetric, due to the asymmetry of the panel cut. Most importantly the impact of surface wave diffraction on the single antenna pattern is significant with a first deep null
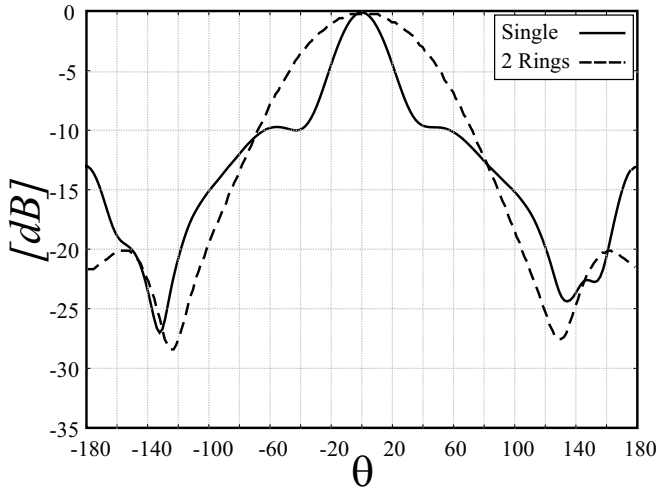
Fig. 8. H-plane radiation pattern measured at the central frequency for the single antenna and the PCS-EBG antenna with two rings.
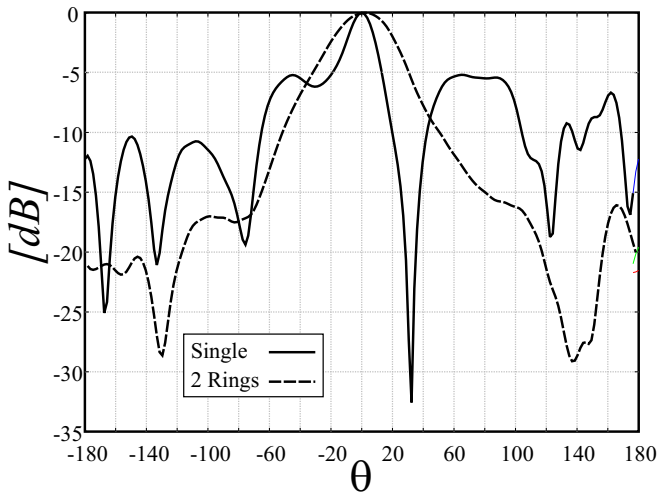

Fig. 9. E-plane radiation pattern measured at the central frequency for the single antenna and the PCS-EBG antenna with two rings.

well inside the 3 dB radiation pattern region.

The same antennas have been simulated with Ansoft Designer which considers an infinite substrate (no edge effects). The gain given by this tool can be interpreted as a measure of the radiation efficiency of the antenna, and is shown in Fig. 10. In the presented designs, the antenna without EBG has a very low gain in the order of 1dB (due to the fact that more than 60% of the power is launched into the TM_0 surface wave and the diffraction at the edge of the substrate is not accounted for). However even if real gain, including edge effects, turns to be higher, it is not controllable thus cannot be used. When the antenna is simulated with the PCS-EBG with 2 rings around it, a significant gain improvement of around 8.5dBs is observed. Already with 2 rings a surface wave efficiency of 90% is obtained, which corresponds to 3dBs of gain improvement. The additional gain improvement is associated to a larger effective area of the antenna.

VI. CONCLUSION

In this paper the use of purely planar circularly symmetric periodic metallic loadings has been proposed to impede the propagation of the TM_0 surface wave in planar printed
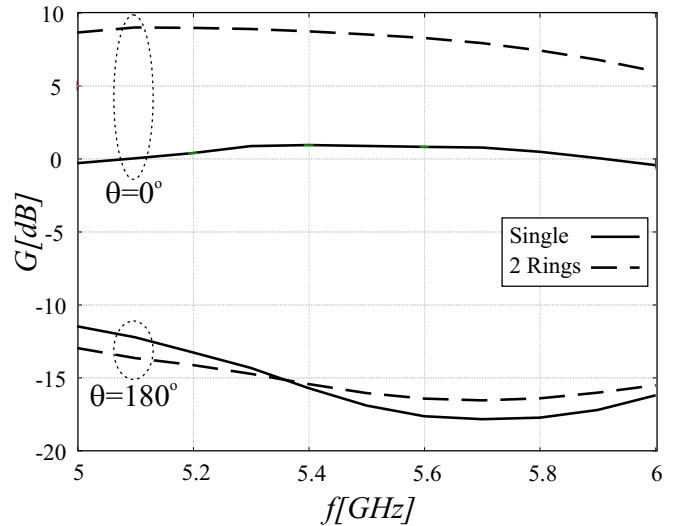

Fig. 10. Simulated gain at broadside and backside for the single antenna and the PCS-EBG antenna with two rings.

structures. The main advantage of the design simplicity is that the performances of the ensemble of antenna and EBG can be easily optimized to meet specific requirements. An antenna with 20% of bandwidth has been presented which does not suffer from surface wave effects. The radius of the PCS-EBG is half of the surface wave length, λ_{TM0}, for maximum radiation bandwidth. This will be demonstrated in further publication.

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