Design of a Fully Planar BC-CSRR SIW-based H-plane Sectoral Horn with a Printed Transition

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Abstract— The Broadside Coupled Complementary Split Ring Resonator Substrate Integrated Waveguide (BC-CSRR SIW) is a fully planar platform for the implementation of millimeter-wave components at a minimal fabrication cost. We present here a new design H-plane sectoral horn Antenna based on the BC-CSRR SIW. A transition of parallel plate strips etched on the same substrate is also designed using parametric finite element simulations, in order to improve matching and radiation characteristics. The composite antenna comprising of the BC-CSRR SIW horn and the matching transition exhibits good return loss performance and directive end fire radiation, while the back radiation is kept small.

***Index Terms*—antenna,Substrate Integrated Waveguide, metamaterials, horn antenna, propagation, measurement.**

I. Introduction

The increasing demands of modern wireless communications for faster data transfer rates highlight the importance of utilizing higher frequency bands. As a matter of fact, the design and implementation of 5G wireless networks have designated millimeter wave frequency bands for possible exploitation, such as 24.25 - 27.5GHz. This has led to a significant interest in developing new component designs capable of supporting high frequency propagation and radiation. However, the availability of cost effective production remains a crucial factor for the success of these new technologies.

In this direction, the metamerial - based Substrate Integrated Waveguide has been proven to be a promising and truly planar candidate offering a reconfigurable platform for the design and integration of the necessary components, such as waveguides and antennas [1]-[4]. The BC-CSRR based Substrate Integrated Waveguide is an alternative Substrate integrated waveguide, based on the use of a periodic structure of Broadside coupled Complementary Split Ring Resonators acting as the side walls for the channeling of the in-plane propagation. This design offers very comparable characteristics to the well established and documented case of the standard Substrate Integrated Waveguide, retaining the advantages of low loss propagation at millimeter wave frequencies and same substrate component integration, while simultaneously removing the need for metallic post vias penetrating the substrate and thus simplifying the fabrication process. However, the substitution of the metallic vias with the BC-CSRRs causes certain implications, as the meta-material periodic structure functions as a virtual electric wall, screening the electric field for certain incidence angles, polarizations and frequencies, which complicates the migration of SIW-based components design to the BC-CSRR SIW platform. Nonetheless, slot antennas based on the BC-CSRR SIW have been presented in [2], [3], offering proof of concept to the overall idea.

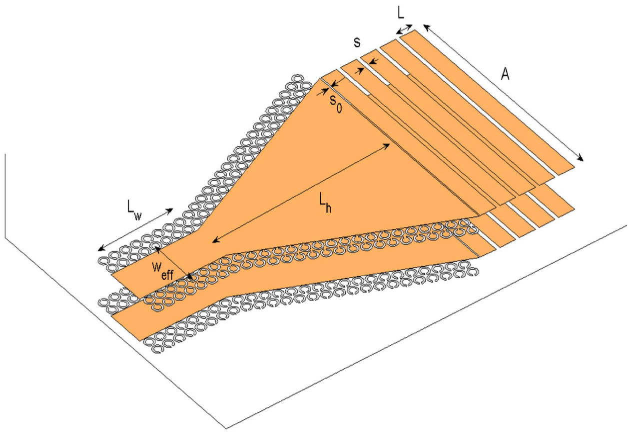

Fig. 1. The BC-CSRR SIW H-plane horn antenna with a transition of five parallel plate strips.

II. Building Blocks Of The BC-CSRR SIW Sectoral H-Plane Horn Antenna

A. The BC-CSRR Substrate Integrated Waveguide

The basis structure of the proposed antennas is the BC-CSRR SIW described in [1][4], which can be regarded as 1D periodic structure consisting of layered unit cells, i.e. a slice of the waveguide with two broadside complementary split ring resonators etched on the top and bottom metal terminations of the substrate. The top view of a single BC-CSRR cell is depicted in Fig 2. The CSRR elements on the two sides of the unit cell exhibit single negative behaviour in terms of effective dielectric permittivity, functioning as an equivalent electric wall for in plane waves and thus restraining propagation through the sides of the waveguide.

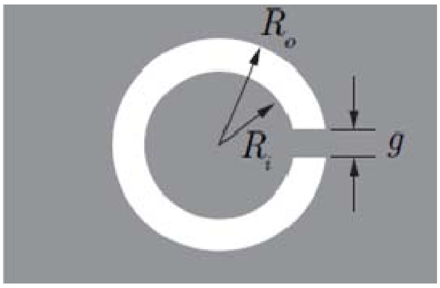

Fig. 2. Top view of the BC-CSRR unit cell

The operation of this waveguide is uniquely determined by its main building block, i.e. a unit cell consisting of two BC-CSRRs placed at each side at a distance of w_{eff}. As a result, the unit cell of the BC-CSRR metamaterial itself is properly designed in order to function successfully at the desired frequencies [4]. An important factor on the latter's behavior is the substrate thickness, as it directly affects the coupling between the BC-CSRR rings. This limits the choice of possible substrates to those of smaller thicknesses as the opposite would diminish the ability of the metamaterial to function as an electric wall, due to the decoupling of the rings at both sides of the substrate. Furthermore, the choice of the printed circuit boards' dielectric permittivity is another important factor for the overall design as it determines the propagation characteristics of the composite waveguide as well as the frequency response of the BC-CSRRs. It must be noted that the design of the waveguide structure is optimized to achieve single-mode operation at the desired band of frequencies.

B. *Substrate Integrated Waveguide Horns*

The basis of the proposed antennas are the sectoral H-plane SIW horn antennas presented in [5],[6], where the flaring of the metallic vias forms the lateral sections of the horn. These antennas exhibit vertically polarized end fire radiation. The problems that arise from this configuration are directly related to the substrate thickness, as the inability to produce a gradual transition on the vertical plane diminishes the matching between the antenna and the air. This intensifies when the substrate has thickness lesser than $\lambda_0/6$, resulting in unwanted radiation and poor matching behavior.

C. *Printed Transition for Matching Improvement*

A solution to this problem is the addition of a transition of parallel-plate elements etched on the same substrate directly after the aperture of the horn. The purpose of this structure is improve the air to horn matching and thus reduce the Return Loss coefficient, while at the same time improve the radiation characteristics by enhancing the Front to Back Ratio. This transition consists of a number of parallel plate strips of length L_i, which are separated by gaps s_i of varying widths. According to [7], the apertures formed between the parallel plates of the matching strips can be considered as the radiating elements of an antenna array along the x axis. The spacing between the elements determines the contribution to the array factor of the individual apertures, while assuming that $L_i >> s_i$, the phase difference is controlled by the length of the parallel plate strips.

This analysis becomes clearer if we examine the case of a horn with a transition of two parallel plate strips. If the two transition elements are separated by a large gap, the first aperture will radiate most of the incoming power, while the second aperture's contribution will be negligible. If, on the other hand, the separation between the two elements is relatively small, most of the radiated power will come from the second aperture, while the first element will function mostly as a resonator. The phase difference of the array elements is controlled by the length L of the parallel plate strips and the Array Factor of the composite antenna is given in [6] as:

$$AF(\theta) = A_1 e^{-j(\frac{2\pi}{\lambda_0}\frac{L}{2}\cos(\theta))} + A_2 e^{ja} e^{-j(\frac{2\pi}{\lambda_0}\frac{L}{2}\cos(\theta))}, \qquad (1)$$

where A_1, A_2 are the amplitudes of the array elements and a the corresponding phase shift. If an appropriate choice of separation gap has been made, we can assume that the amplitudes of both elements are equal and as a result the radiation pattern of the antenna will depend mostly on the choice of L. This means that we can modify the H-Plane directivity of the horn and cancel the back radiation by properly selecting matching strip lengths so as the array factor is zeroed at θ = 180º. The shortest length of the matching strip for which this becomes true is given in [6] as:

$$L = \frac{\lambda_c}{2(1+\sqrt{\varepsilon_{rpp}})}, \qquad (2)$$

where λ_c is the wavelength for which we want to cancel back radiation and ε_{rpp} the effective permittivity of the parallel plate waveguide for the given substrate. However, considering that even if the choice of the separating gap is optimal, radiation losses will cause the amplitudes of the array elements to differ, it is evident that the above analysis can lead only to minimization of the backward radiation and not to complete cancellation.

III. THE BC-CSRR H-PLANE HORN ANTENNA

Section II highlighted the importance of the thickness of the substrate on Electric field screening of the periodic BC-CSSR structure as well as the defective matching of a thin substrate horn with air. The problem that arises comprises of a trade-off analogy between the desired operation of the metamaterial SIW and the radiation characteristics of a corresponding antenna. As a result, the design process for the proposed BC-CSRR SIW sectoral H-plane horn antenna follows the guidelines of the SIW horn antenna with the additional parallel plate transition.

The proposed configuration is depicted in Fig. 1 and it is comprised of a feed BC-CSRR Waveguide and the horn along with the matching transition.

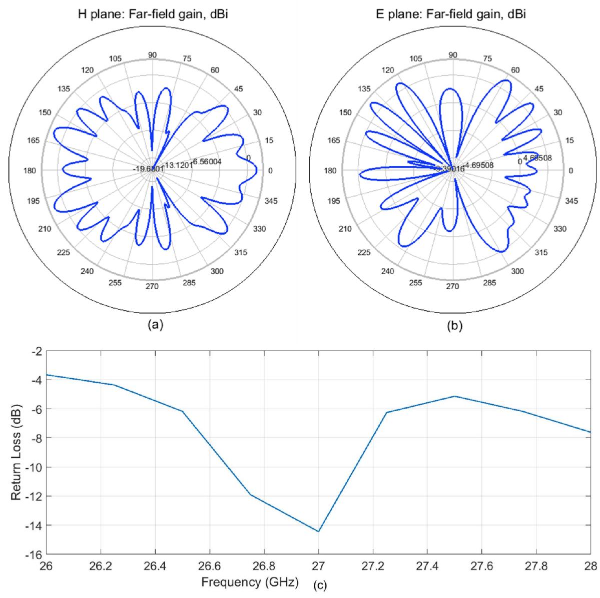

Fig. 3. Simulation Results for the BC CSRR SIW H-plane horn antenna without a matching transition. (a) The H-plane far field gain at 26.75GHz. (b) the E-plane far field gain at 26.75GHz. (c) Return Loss.

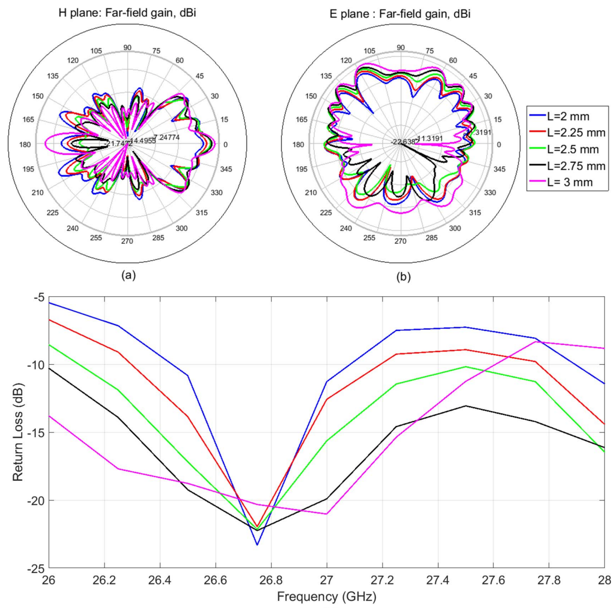

Fig. 4. Parametric simulation results of the BC-CSRR SIW H-plane horn antenna with a transition of two elements for different parallel plate strip lengths. (a) The H-plane far field gain at 26.75GHz. (b) the E-plane far field gain at 26.75GHz. (c) Return Loss.

The metamaterial SIW was designed according to [4] with dimensions that guarantee single mode propagation, while the dimensions of the horn were selected following the same principles as conventional rectangular waveguide horns [8]. As a result, most of the attention was reserved for the design of the parallel plate transition. According to [5], regardless of the choice of the rest of the transition parameters, one separation gap should have length much smaller than λ_0 in order to achieve lower return losses at a resonant frequency. The gap we selected for this reason was s_0, the separation between the horn aperture and the first matching strip, while the central design frequency for the antenna was set to 26.75GHz. The rest of the transition parameters were investigated and determined via parametric COMSOL Multiphysics simulations, using the design guidelines of section III as a starting point.

All the antennas were designed for integration on the commercially available Taconic substrate of 0.8001mm thickness, 2.2 dielectric permittivity and 0.0001 loss tangent. The dimensions of the BC-CSRR SIW waveguide feed and the horn are given in Table I and Table II respectively.

The BC-CSRR H-plane horn was analyzed without any kind of matching transition to provide a reference. The Return Loss coefficient and the horizontal and vertical plane directivity patterns are depicted in Fig. 3. Clearly, the antenna has poor radiation characteristics and narrow bandwidth, as it was expected due to the mismatch of the thin substrate horn and the air.

TABLE I. BC-CSRR SIW DIMENSIONS

Dimensions in mm	
BC-CSRR Ring Outer Radius R_0	0.84
BC-CSRR Ring Inner Radius R_i	0.54
BC-CSRR Ring gap g	0.3
BC-CSRR SIW width W_{eff}	6.5
BC-CSRR SIW length L_w	15

TABLE II. BC –CSRR HPLANE HORN DIMENSIONS

Dimensions in mm	
Horn Length L_h	32.5
Horn Aperture A	36

IV. PARAMETRIC DESIGN OF THE MATCHING TRANSITION

Initially, we examined the influence of the parallel plate strip's length L on the radiation and matching characteristics of the BC-CSRR SIW sectoral horn with a transition of two elements and gaps s_0 = 0.2mm and s = 0.5mm. The search for a suitable L was conducted for values around 2.5mm, which is the shortest length for minimal back radiation according to (2) and the results, are shown on Fig. 4.

The Return Loss validates the improved matching of the composite antenna as all five different solutions exhibit a deep resonance at the desired frequency. There is also a proportional relationship between the antenna bandwidth and the matching strip length, resulting in a highly satisfactory bandwidth of 1 GHz, taking into account the waveguides' relatively limited bandwidth, for L=3mm. The final choice of L is determined by examining the horizontal far field gain, which confirms the importance of the parallel plate strip length on the radiation pattern.

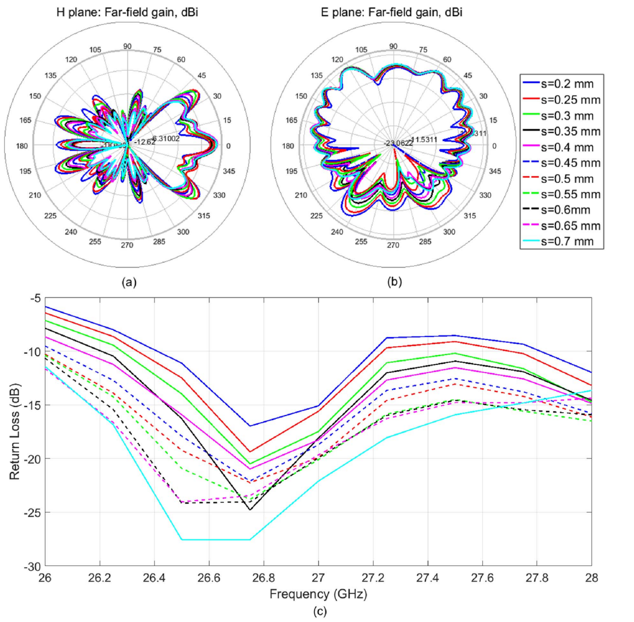

Fig. 5. Parametric simulation results of the BC-CSRR SIW H-plane horn antenna with a transition of two elements for different parallel plate strip lengths. (a) The H-plane far field gain at 26.75GHz. (b) the E-plane far field gain at 26.75GHz. (c) Return Loss.

On the other hand, the addition of the parallel plate strips seems to have minimal effect on the radiation pattern on the vertical plane. This behavior was of course expected, since the transition functions as a plane flare needed for the manipulation of the vertical radiation pattern. The array analogy of [7] is validated, as the length which reduces the back radiation on the horizontal plane mostly is the one calculated by (2). However, taking into account that the choice of L=2.75mm exhibited similarly good radiation characteristics and superior matching behavior, it was selected for the transition elements of the subsequent parametric solutions.

The next step in configuring the antenna design was determining the effect of the gap size s on the overall performance of the antenna. As it was described in Section III, adjusting the distance between the matching strips is expected to have a direct influence on the array factor of the composite structure as it will regulate the power deposited at each element. The results of the parametric analysis are depicted in Fig. 5. The Return Loss Coefficient reveals a relationship similar to that of L, since longer gaps improve the matching performance of the transition. This can be explained by considering the transition of the closely located parallel plate strips not as an array of apertures but as a series of resonators. In this case, the response of the transition can be approximated by the Coupled Resonator Model described in [1] and the reduced ratio of s / L leads to a reduced bandwidth. The longer gaps seem to provide better radiation characteristics as well. However, the effect of the gap size on the radiation pattern of the antenna is minimal, if it is actually long enough to maintain matching conditions.

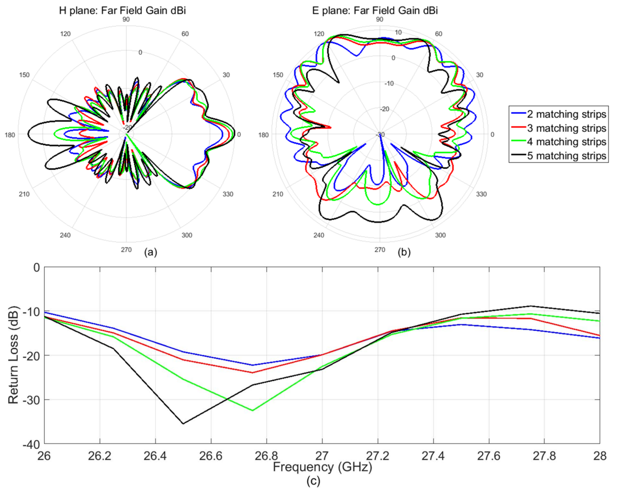

Fig. 6. Parametric simulation results for the BC-CSRR SIW H-plane horn antenna with transitions of different number of elements. (a) The H-plane far field gain at 26.75GHz. (b) the E-plane far field gain at 26.75GHz. (c) Return Loss.

The last parameter to be examined was the number of the parallel plate strips contributing to the matching transition. The transition was tested for up to five elements of $L = 2.75mm$ and $s = 0.5mm$ and the comparative results are depicted in Fig. 6. The matching performance of the transition improves drastically with the number of its elements increasing, achieving both wider bandwidths and lower reflection. The same can be inferred in terms of the front-end directivity of the antenna, as the additional elements appear to function as directors increasing the front-end gain, acquiring the maximum value for the largest number of strips. This positive impact however is reversed when examining the radiation of the antenna at the back end. Regarding the transition as an antenna array of apertures, this effect could be attributed to the difference between the amplitudes of the individual elements, which becomes greater between the furthest elements of the array.

The compromise between increased front-end gain, high Front to Back Ratio and matching performance is best achieved for the transition of three matching parallel plate strips, which exhibits highly satisfactory behavior in all three parts. Finally, the radiation efficiency of this configuration was calculated accounting for all loss mechanisms and is depicted in Fig. 7. The overall computed efficiency is considered satisfactory, given the expected increased losses at the frequency band under study.

Consequently, the results of the parametric design process reaffirm the good performance of the composite antenna in the frequency range of interest. The maximum of the far field gain of the antenna was computed at 11.9dBi and is nearly towards the end-fire direction. The proposed antenna is currently under fabrication process and, although the substrates considered are of high quality, a series of low-cost fabrication approaches are considered in parallel, including photosensitive printing and etching based on dry-film negative photoresists.

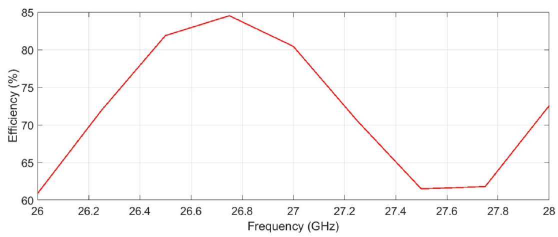

Fig. 7. Antenna Efficiency of the BC-CSRR SIW H-plane sectoral horn with a transition of three parallel plate strips

CONCLUDING REMARKS

We have presented a new design for a fully planar end fire composite horn antenna based on the BC-CSRR Substrate Integrated Waveguide. The proposed configuration exhibits very good matching performance and directive radiation characteristics, while its simple and cost-effective fabrication render it as a promising design for realistic millimeter wave applications.

ACKNOWLEDGMENT

This research is carried out / funded in the context of the project "Development and implementation of an integrated platform for fully planar low-cost circuits for 5G, Internet-of-Things and THz Communications technologies" (MIS 5005207) under the call for proposals "Supporting researchers with emphasis on new researchers" (EDULLL 34). The project is co-financed by Greece and the European Union (European Social Fund- ESF) by the Operational Programme Human Resources Development, Education and Lifelong Learning 2014-2020.

Ευρωπαϊκή Ένωση
European Social Fund

Operational Programme
Human Resources Development,
Education and Lifelong Learning
Co-financed by Greece and the European Union

ΕΣΠΑ
2014-2020
ανάπτυξη - εργασία - αλληλεγγύη

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