Directivity Improvement of a 94GHz LTCC Integrated Pyramidal Horn Antenna Using EBG Structure

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***Abstract*—There is a strong interest to implement antenna-in-package (AiP) systems for a cohort of applications such as imaging, beamforming, integrated transceivers, and radars. Substrate integrated pyramidal antennas (SIPA) are valuable AiP candidates owing to their small form factor, integration ease, and high gain. However, height reduction and substrate integration can drastically reduce the overall directivity of such antennas and hence limit their potential applications. This degradation is mainly due to surface waves propagating and radiating on the dielectric. For the first time in this paper, we present a 94GHz low temperature cofired ceramic (LTCC) integrated pyramidal horn antenna. To prevent transverse magnetic (TM) surface waves, a mushroom type electromagnetic bandgap (EBG) structure is implemented in the surrounding of the horn. The LTCC fabrication is particularly suitable for this kind of structure. Since only a single *well* is needed to fabricate the horn and the EBG structure, complexity and cost are minimized. The combined antenna with EBG surrounding leads to approximately 1.8dB improvement in maximum directivity. Concurrently, the 3dB beamwidth is reduced by 10° for the E-Plane and 20° for the H-Plane.**

***Index Terms*—Low Temperature Cofired Ceramic (LTCC), Antenna in Package, 94GHz, Electromagnetic Band-Gap (EBG)**

I. Introduction

Low temperature co-fired ceramic (LTCC) is a low cost and high density integration packaging technology. LTCC also enables multilayer antenna fabrication and offers better control on the number of layers as compared to classical printed circuit boards (PCB) [1]. Therefore, LTCC is a convenient fabrication approach for integrated pyramidal antennas where geometrical feature control is important. Nevertheless, LTCC fabrication suffers from a number of drawbacks. For instance, a commonly used substrate, the DuPont 9K7 Tape ($\epsilon_r = 7.1$), imposes stringent limitations on the fabrication which can drastically impact the performance of horns and leads to parasitic excitations. Also, the layer-by-layer implementation is done using *via* technology to create the integrated structure. As such, only vias are used to create the integrated horn walls inside the substrate. These imperfect walls cause leakage that can potentially excite parasitic fields on the dielectric and lead to back radiation and directivity loss.

In this paper, we present the fabrication process analysis of a novel substrate integrated pyramidal horn antenna operating at 94GHz. To reduce the edge diffraction, we place a high impedance surface ring around the aperture periphery using a mushroom EBG [2]. The latter was chosen for its design simplicity.

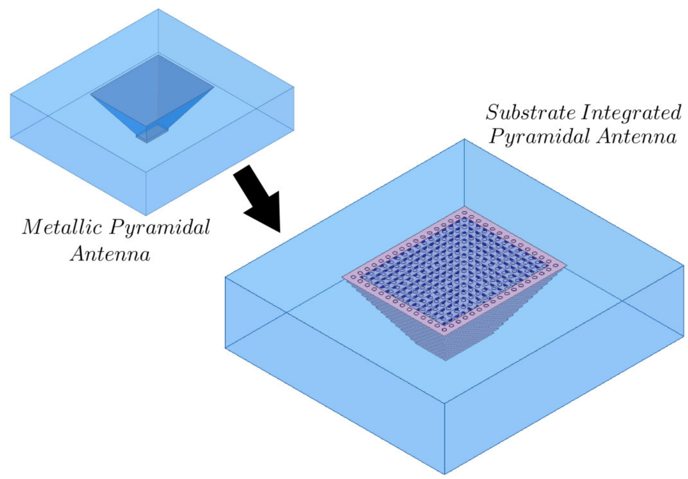

Fig. 1. Substrate Integrated Pyramidal Antenna (SIPA) on LTCC. In the top left, we show an equivalent horn antenna using perfect metallic walls.

II. Design and Fabrication Process Consideration

A. Integrated Horn Antenna

Fig. 1 presents the rendering an integrated pyramidal horn antenna operating at 94GHz. On the upper left we show an equivalent perfect metallic horn antenna, designed to match the requirement for the LTCC fabrication. The walls of the metallic horn were discretized according to the *fired* thickness of the LTCC layers. That is, the via horn is a stepped version of the smooth surface horn. The pitch between two successive *vias* is carefully chosen to minimize leakage and the current flow inside and outside the antenna. This leakage can excite undesired diffracted fields that may lead to directivity loss and deformation of the radiation pattern.

The feeding of the antenna is based on a dielectric loaded WR-10 perfect metallic waveguide of dimensions $a = \frac{2.54}{\sqrt{\epsilon_r}}$ mm and $b = \frac{1.27}{\sqrt{\epsilon_r}}$ mm. These dimensions were chosen based on classical waveguide equations [3]. Fig. 2 depicts a side view of the horn antenna showing the placed vias at every layer with respect to two slopes P_x along the x and P_y along y axes :

$$P_x = \frac{2H}{A-a} \quad (1)$$

$$P_y = \frac{2H}{B-b} \quad (2)$$

where A and B refer to the horn's aperture size along the x and y direction respectively. Also H is the total horn height. Referring to Fig. 2, H is an integer multiple of h, the depth of the via, i.e. $H = 2Nh$. Hence, (1) and (2) become :

$$P_x = \frac{2Nh}{A-a} \quad (3)$$

$$P_y = \frac{2Nh}{B-b} \quad (4)$$

In the above, N is the number of layers comprising the horn. In our case, we use $N = 15$. To totally ensure contact between the layers, each via lies on a $\frac{d}{2}$ pad.

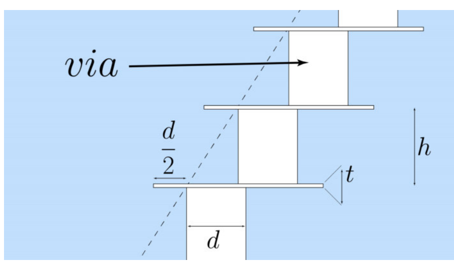

Fig. 2. LTCC horn generation using *vias* to create the inner surface.

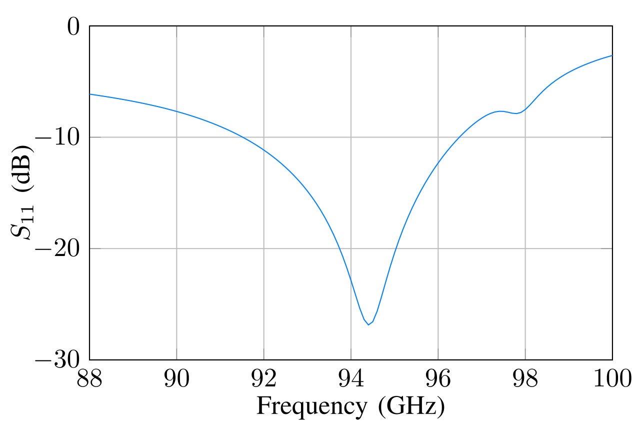

Fig. 3. S_{11} of the Substrate Integrated Pyramidal Antenna (SIPA) showing good matching from 91.5GHz to 94.4GHz.

For the designed and fabricated pyramidal antenna we achieved a 5GHz bandwidth, (from 91.5GHz to 96.5GHz) as depicted Fig.3.

The radiation pattern, presented in Fig. 4, shows a considerable back radiation with a main back lobe located at $\theta = 180°$. Notably, the front-to-back ratio is slightly higher than 13dB and the beamwidth in both planes is approximately 62° for the E-plane and 69° for the H-plane.

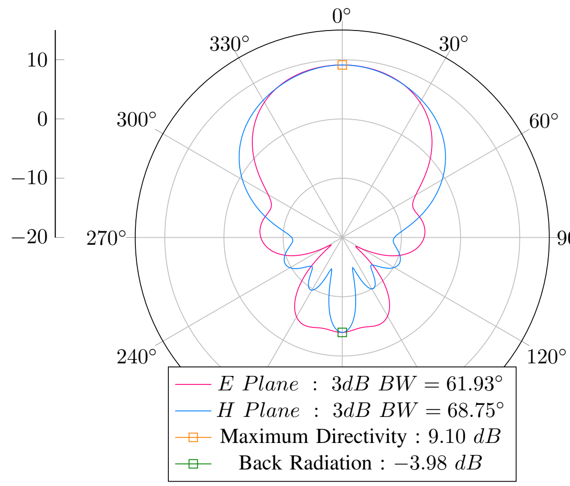

Fig. 4. SIPA radiation pattern showing considerable back radiation and wide 3dB beamwidth in both E and H Planes.

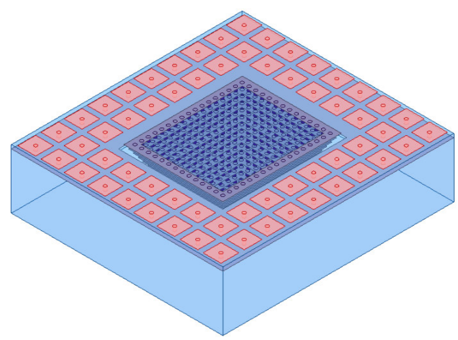

Fig. 5. SIPA with EBG surrounding.

To improve the front-to-back ratio and achieve narrower beamwidth, a straightforward approach consists of incorporating an integrated metallic plane on the back of the horn. However, such solution does not improve the directivity. A more attractive solution is using EBG structure to prevent edge diffraction along the aperture's periphery. This is discussed below.

B. Simple Electromagnetic Band-Gap (EBG) Structure

EBG structures are periodic and frequency selective structures. One of the earliest EBG periodic surfaces is that of the mushroom structure [4], as depicted in Fig. 6. This structure is equivalent to a LC circuit. Notably, it was designed to have a cut-off frequency and a maximum impedance at a frequency slightly lower than 94GHz to ensure that the 94GHz edge diffractions are suppressed. The subject resonance frequency of the EBG is given :

$$f_r = \frac{1}{2\pi\sqrt{LC}} \quad (5)$$

where L and C are the equivalent inductance and capacitance, respectively. Here :

$$L = \mu_0 h_e \quad (6)$$

$$C = \epsilon_0 \frac{1+\epsilon_r}{\pi}.W_e.cosh^{-1}(\frac{W_e}{g_e}+1) \qquad (7)$$

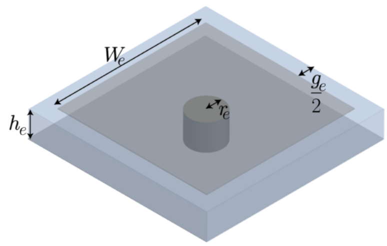

Fig. 6. EBG unit cell mushroom geometry for placing around the substrate integrated pyramidal antenna (SIPA) to suppress diffraction and backward lobes.

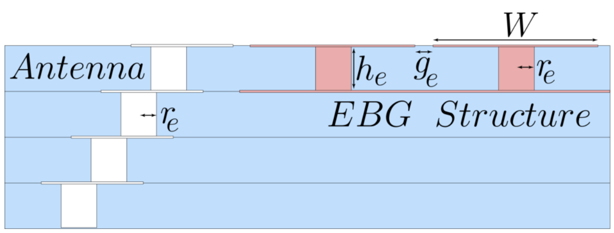

Fig. 7. Side view of the SIPA with EBG structure.

where μ_0 is the free space permeability, h_e the height of the substrate, W_e the width of the patch forming the mushroom and g_e is the gap between two successive EBG cells.

III. Performances

The EBG structure is then integrated around the horn antenna. We use two rows of unit cells to ensure diffraction suppression from the horn aperture's periphery. As depicted in Figs. 5 and 7, the EBG cells are located at the top of the 15 layer structure horn antenna.

The radiation pattern of the SIPA horn with the EBG surrounding is depicted in Fig. 8. As seen, back radiation is significantly reduced by 5dB and 8dB in the E and H-Planes, respectively. The two back lobes are located at $\theta = 150°$ and $\theta = 210°$. The 3dB beamwidth is also reduced and is around $53°$ and $49°$ in both E and H-planes, respectively. This is a reduction of the beamwidth of about $10°$ to $20°$ as compared to the case without the EBG ribbons around the aperture. The resulting gain improvement is about 1.8dB.

IV. Conclusion and Remark

We presented a 94GHz LTCC approach to fabricate an integrated pyramidal horn antenna with integrated EBG ribbons around its aperture to suppress undesired diffraction. The EBG ribbons around the LTCC pyramidal horn led to significant reduction of the backward radiations lobes. As a result, the overall directivity increased by 1.8dB at 94GHz. At the meeting, we will present fabrication details and challenges. Measurements will also be provided.

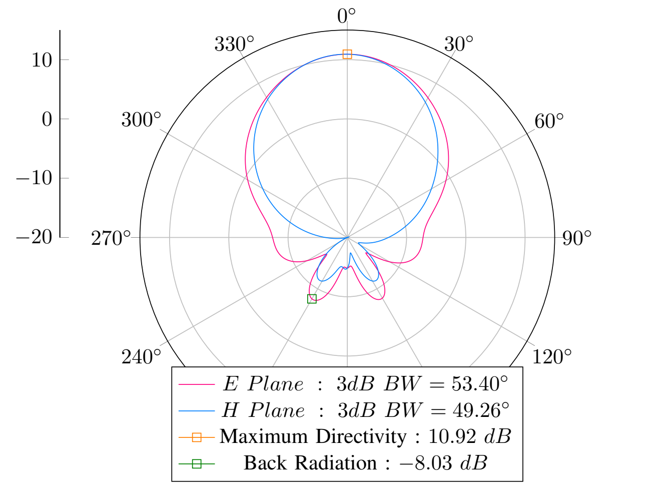

Fig. 8. Radiation pattern of the SIPA with EBG surrounding showing back radiation improvement and narrower 3dB beamwidths in both E and H Planes.

References

[1] N. Ghassemi and K. Wu, "Millimeter-Wave Integrated Pyramidal Horn Antenna Made of Multilayer Printed Circuit Board (PCB) Process," IEEE Transactions on antennas and propagation, vol. 60, No. 9, pp. 4432–4435, October 2012.

[2] W. E. McKinzie, D. M. Nair, B. A. Thrasher, M. A. Smith, E. D. Hughes, and J. M. Parisi , "60 GHz Patch Antenna in LTCC with an Integrated EBG Structure for Antenna Pattern Improvements," IEEE Antennas and Propagation Society International Symposium, pp. 1766–1767, July 2014.

[3] D. M. Pozar, "Microwave Engineering", Fourth Edition, John Wiley & Sons, inc., publication, 2012

[4] D. F. Sievenpiper, "High-impedance electromagnetic surfaces, Ph.D. Diss., Dept. of Electrical Engineering, University of California, Los Angeles, 1999.