Parabolic cylindrical reflector antenna at 60 GHz with line feed in gap waveguide technology

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***Abstract*—A parabolic cylindrical reflector antenna is proposed in this paper for wireless multi-gigabit communications at 60 GHz. The line feed is realized by a power distribution in parallel plate waveguide (PPW). Inside the PPW waveguide there are metal pin rows forming the contours of an H-plane horn structure in front of a parabolic reflector, where we see possible mechanical advantages in not requiring metal contact of the pins to more than one metal plate. They will still work as a total reflecting wall by making use of the same stopband features as in gap waveguide technology. The result is a low loss, low cost and very versatile 60 GHz antenna with high gain. The electrical design for maximum aperture efficiency and minimum loss is explained.**

Index Terms*—*reflector antenna; gap waveguide; mm-wave antennas

I. INTRODUCTION

The growing interest of telecommunication applications at the millimeter and sub-millimeter wave-bands demands an immediate and fast development of antennas and circuits at those frequencies. Existing technologies exhibit some deficiencies at frequencies over 30 GHz. Microstrip circuits are appropriate for integration with active MMIC components, but they suffer from higher losses with increasing frequency as well as from the presence of cavity resonances when packaged. Hollow waveguides are resorted for low-loss applications, but they are not fit for integration. Moreover, for high performance they become difficult to manufacture, and thus, high-cost. As a consequence of the above, new technologies have come out as alternatives. An example is the Substrate Integrated Waveguide (SIW) [1]. SIW has been widely used for a large range of mm-wave devices [2], but it still shows significant losses due to wave propagation in substrate. A more recent approach is the gap waveguide technology [3]. Unlike SIW, gap waveguides support waves in the air gap between two metal plates. One of the plates is provided with a texture, in the form of e.g. a bed of nails, in order to create high surface impedance, which in turn enforces a cut-off for the parallel-plate waveguide (PPW) modes [4]. In the same plate, metal ridges in between the nails provide a path to the waves. This propagation path can alternatively be provided by a microstrip line lying on the bed of nails, or by a groove in between the nails [5]. Gap waveguides are realized between two metal plates that do not require any electrical contact between them. The main advantages of gap waveguides are that they have low loss, represent circuits already packaged and shielded [6], and that they are easy to manufacture and suitable for integration with active components. Therefore, they represent a promising technology for mm-wave applications.

On the other hand, wireless multi-gigabit communications at 60 GHz require high gain broadband antennas. Arrays and reflectors are the most common solutions. The gain and overall efficiency of an array antenna depends mainly on the losses of the feed network, and thus, on the technology used for it, because the aperture efficiency can be almost 100% when using a parallel fully branched (i.e. corporate) feed network. Efficiencies of reflector antennas are usually superior due to their low losses, but reflectors are bulky, heavy, and inconvenient for reconfigurable beams, multi-beam or scanning applications. In this paper, we propose a solution that keeps the advantages of reflector antennas and at the same time has the versatility needed for multiple beams in one plane. Our solution makes use of the gap waveguide concept, and it has been conceived for gap waveguide circuit integration. In the literature, we can find an example of a multi-layered phased array antenna at 76 GHz developed in Japan using gap waveguide technology [7]. Our reflector solution is a simpler alternative easily extendable to multiple beams in one plane.

The present paper makes use of the characterization methods for parabolic cylindrical reflectors presented in [8]-[9].

II. DESCRIPTION

The proposed antenna consists of a parabolic cylindrical reflector, whose line feed is created by means of a planar parabolic reflector formed in between two parallel metal plates (see Fig. 1). This paper only shows the case of an antenna with one fixed beam, but the possibility of multi-beam or reconfigurable beam antenna is straightforward for the proposed solution. Using an array as a feed for the parabolic reflector in the parallel-plate waveguide (PPW) or replacing this parabolic reflector by a lens (Lunenberg, Rotman, etc.) in PPW provides a large versatility to the proposed solution for very different applications.

For the aim of compactness, we have chosen a subtended angle of 90 degrees for both reflectors (the cylindrical one and the one in PPW), that results in a square aperture of size 14 cm × 14 cm. The parabolic reflector in PPW can be realized by a metal wall with parabolic shape perpendicular to the PPW plates that goes from the top to the bottom plates of the PPW. But at 60 GHz, the leakage through the wall will be unacceptable unless a very good electrical contact exists between the parabolic wall inside the PPW and the plates of the PPW itself. This is difficult to achieve at mm-wave frequencies. Therefore, we use here instead the gap waveguide concept to create the parabolic reflector in PPW. The parabolic metal wall is then replaced by a virtual wall, which is created between the plates by using a row of pins but without the need of electrical contact between the pins and one of the plates. The reason is that metal pins of λ/4 length in one of the plates of the PPW forces a cut-off for the parallel-plate modes as far as the air gap between the top of the pins and the second plate is smaller than λ/4. Each row of pins attenuates the fields about 20 dB, so that two or three rows of pins are usually enough to form the virtual wall. In this way, the manufacturing is simplified and the production cost is reduced.

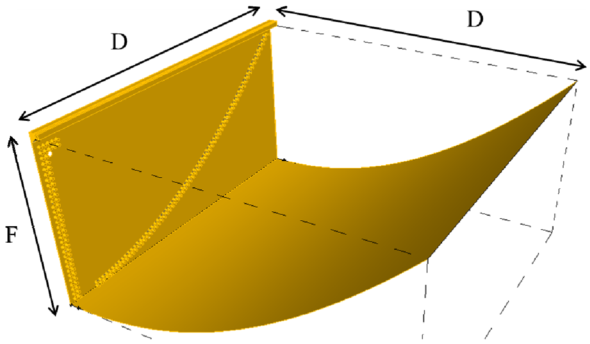

Figure 1. Sketch of the parabolic cylindrical reflector. Line feed is created by means of a parabolic reflector formed in between two parallel metal plates representing a PPW. One of these metal plates has been removed in order to see the line of pin rows forming the parabolic reflector inside the PPW.

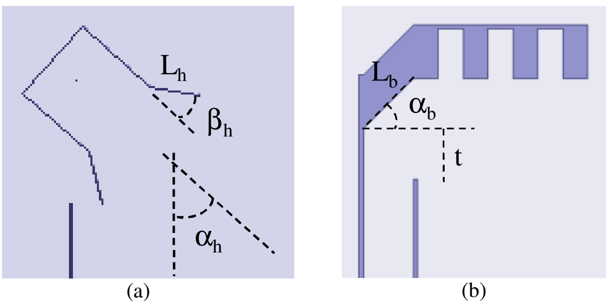

Figure 2. Detail of the feed for the longitudinal (a) and transverse (b) problems: (a) H-plane horn in PPW, (b) aperture with corrugated wall.

The parabolic reflector in PPW is fed by an H-plane horn in its focal point (see Fig. 2a). The horn is formed inside the PPW in the same way as the parabolic reflector, i.e., by using pins. A virtual wall created by pins extending from the feed horn to the edge of the parabolic wall is also used to avoid leakage and prevent spillover, as can be seen in Fig. 1. The field propagated from the horn and reflected by the reflector in PPW is depicted in Fig. 3. The parabolic reflector in PPW generates a longitudinal aperture field that will be radiated towards the parabolic cylindrical reflector. This is done through an aperture at the edge of the PPW and a 90° bend with a corrugated wall (see Fig. 2b), similar to the hat feed [10], but for a cylindrical 2-D geometry rather than a rotationally symmetric one.

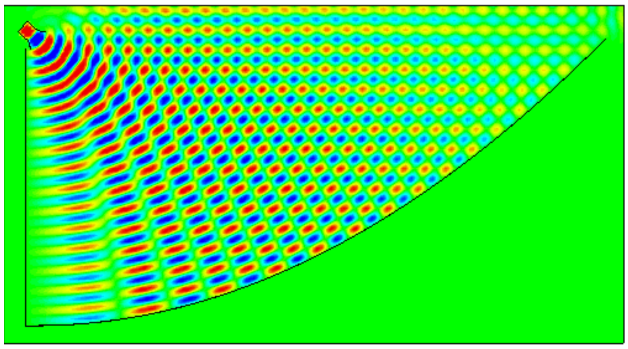

Figure 3. Propagated field in the planar parabolic reflector in PPW.

III. Design

For the initial design of the parabolic cylindrical reflector antenna, the problem is divided in two problems (longitudinal and transverse problems).

The **longitudinal problem** is the planar parabolic reflector in PPW. We do not consider pins at this stage, only metal walls inside the PPW. The design of this problem deals with finding the position and geometry of the feed horn in PPW that maximizes the aperture efficiency. The aperture efficiency and sub-efficiencies have been calculated from the radiation pattern of the feed inside the PPW following the formulas given in [8]. For this design, the aperture efficiency, η_{ap}, was assumed to be expressed by

$$\eta_{ap} = \eta_{il}\eta_{sp}\eta_{ph} \tag{1}$$

where η_{il}, η_{sp}, and η_{ph}, are the illumination, spillover, and phase sub-efficiencies, respectively, that can be written as

$$\eta_{il} = \frac{F}{D}\frac{\left[\int_0^{\pi/2}\left|G(\phi)\right|/\cos(\phi/2)\,d\phi\right]^2}{\int_0^{\pi/2}\left|G(\phi)\right|^2 d\varphi} \tag{2}$$

$$\eta_{sp} = \frac{\int_0^{\pi/2}\left|G(\phi)\right|^2 d\phi}{\int_0^{2\pi}\left|G(\phi)\right|^2 d\phi} \tag{3}$$

$$\eta_{ph} = \frac{\left|\int_0^{\pi/2} G(\phi)/\cos(\phi/2)\,d\phi\right|^2}{\left[\int_0^{\pi/2}\left|G(\phi)\right|/\cos(\phi/2)\,d\phi\right]^2} \tag{4}$$

where $G(\phi)$ is the radiation pattern of feed, in this case an H-plane horn in PPW, F is the focal distance, and $D=2F$ is the length of the aperture of the parabolic reflector in PPW. Other sub-efficiencies are considered negligible at this stage.

Efficiencies can alternatively be calculated from the aperture field distribution along the aperture with corrugated wall radiating towards the exterior parabolic cylinder. Nevertheless, the efficiencies used here for the design are calculated from the radiation pattern of the feed using the formulas (1)-(4).

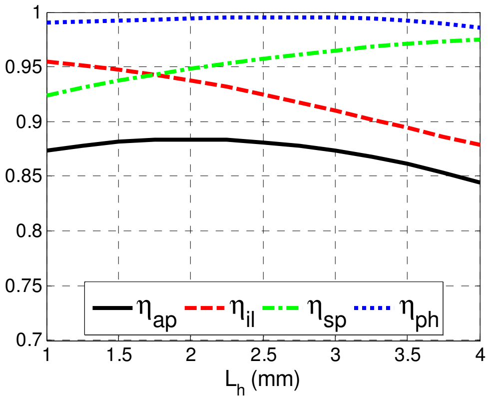

Figure 4. Efficiencies as a function of the length L_h of the H-plane horn in PPW.

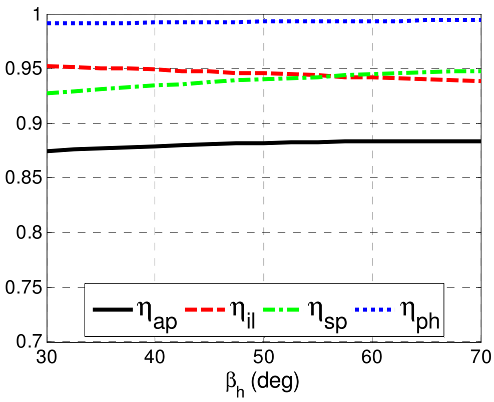

Figure 5. Efficiencies as a function of the angle β_h of the H-plane horn in PPW.

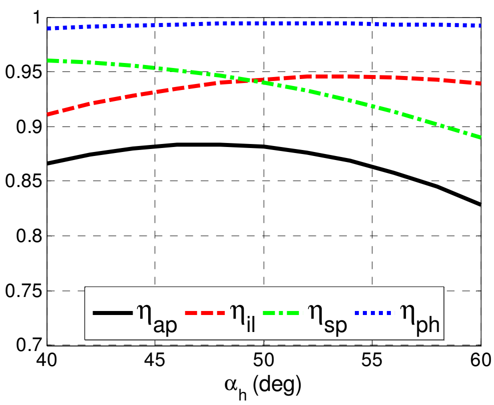

Figure 6. Efficiencies as a function of the angle α_h,which indicates the orientation of the H-plane horn with respect to the reflector in PPW.

On one hand, the location of the feed horn that provides maximum phase efficiency is found. On the other, shape and orientation of horn are the optima to make the product of illumination and spillover efficiencies ($\eta_{il}.\eta_{sp}$) maximum. Regarding to the shape of horn, two parameters were considered for the design, the length L_h and the angle β_h. The angle α_h, which indicates the orientation of the horn with respect to the reflector, was also optimized (see Fig. 2a). Figures 4-6 show how the efficiencies vary as a function of the above-mentioned parameters.

The **transverse problem** is the cylindrical parabolic reflector, which has been assumed to be infinitely long at this stage, so that it is equivalent to a PPW with perfect magnetic conducting (PMC) plates. The design of this problem is very similar to the previous one (except for the opposite polarization between the plates), and deals with finding the position of the line feed and the geometrical parameters of the aperture and corrugated wall geometries that give maximum aperture efficiency.

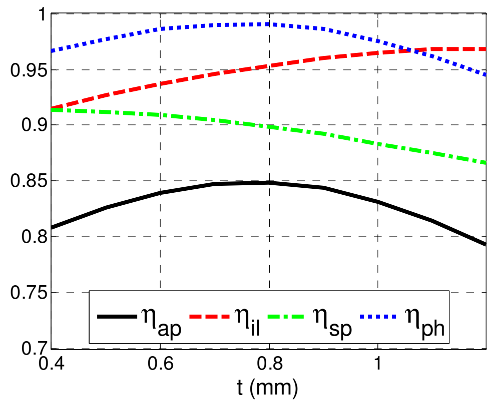

Figure 7. Efficiencies as a function of the distance t in the aperture at the edge of the PPW and 90° bend with corrugated wall.

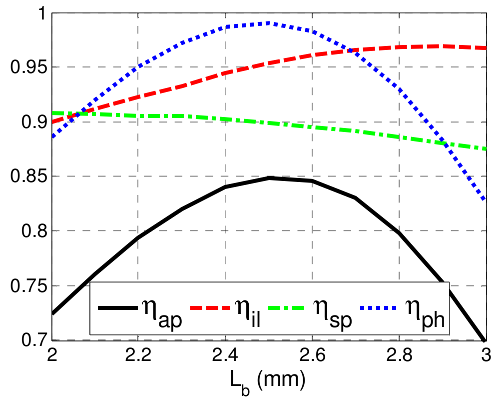

Figure 8. Efficiencies as a function of the length L_b in the aperture at the edge of the PPW and 90° bend with corrugated wall.

As for the longitudinal problem, the location of the line feed that provides maximum phase efficiency is found. Then, the geometrical parameters of the aperture and 90° bend with corrugated wall are chosen the optima that maximize the product $\eta_{il}.\eta_{sp}$. The variations of the efficiencies as a function of the most significant geometrical parameters (t, L_b, and α_b) that are shown in Fig. 2 b are depicted in Figures 7-9.

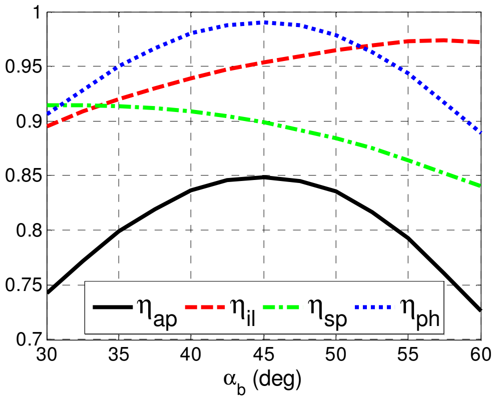

Figure 9. Efficiencies as a function of the angle α_b in the aperture at the edge of the PPW and 90° bend with corrugated wall.

A total efficiency of 70% has been computed for the initial design. This efficiency has been obtained as the product of the aperture efficiencies for the transverse and longitudinal problems.

IV. Simulation Results

Once the initial design of the parabolic cylindrical reflector antenna was obtained, it was analyzed completely including PPW, corrugated line feed and cylindrical reflector using CST Microwave Studio (see Fig. 10).

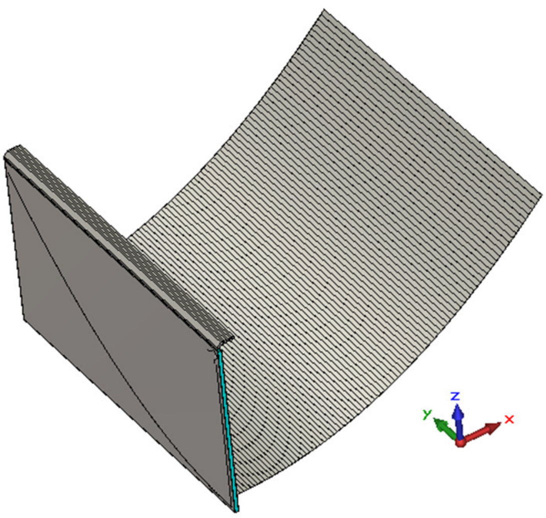

Figure 10. CST model of the initial design of the proposed antenna for high gain at 60 GHz.

Two main cuts of the radiation pattern (ϕ=0° and ϕ=90°) at the center frequency of 61.5 GHz can be seen in Figures 11-12. Here, the co-polar and cross-polar components are depicted. A big sidelobe with maximum level close to θ=90° of around 17 dBi is observed in Fig. 11. It is actually more than 20 dB below the main lobe. This sidelobe is caused by the spillover due to direct radiation from the line feed. Cross-polar component is completely negligible.

A maximum directivity of 38.5 dBi at broadside, and a total efficiency of 65.6 % were computed.

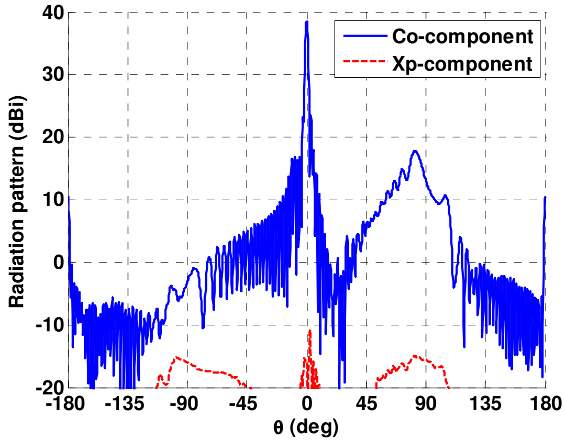

Figure 11. Radiation pattern cut in transverse direction (ϕ=0°) at 61.5 GHz.

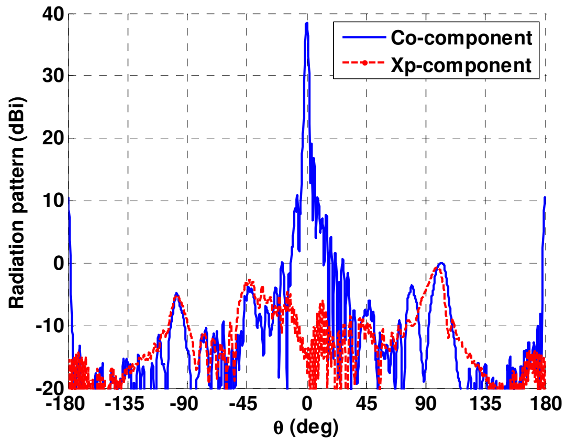

Figure 12. Radiation pattern cut in longitudinal direction (ϕ=90°) at 61.5 GHz.

A prototype of this initial design is being manufactured. Measurements will be shown at the conference.

The final design of the antenna proposed in this paper uses pins instead of metal walls inside the PPW, as it is explained in Section II. Thus, it will make use of the stopband features as in gap waveguide technology. This final design is underway, and PO-MoM will be used for the calculations. Simulation results will be shown at the conference.

V. Conclusions

A parabolic cylindrical reflector antenna has been proposed for multi-gigabit communications at 60 GHz. The line feed is generated through the aperture of a planar parabolic reflector in PPW, which is realized using the gap waveguide concept; therefore no electrical contact between the plates is needed.

The antenna is non-planar, but can still be compact enough for some applications, with a total size of 14 cm × 14 cm × 7 cm. And, it is less lossy than planar solutions, which require a feeding network. The proposed structure has been conceived for gap waveguide circuit integration; and due to its large versatility it can be used for many different applications (multi-beam, scanning, etc.). The sidelobes are very low in the horizontal plane (YOZ plane) (Fig. 12).

REFERENCES

[1] D. Deslandes and K. Wu, "Integrated microstrip and rectangular waveguide in planar form," in IEEE Microwave and Wireless Components Letters, vol. 11, no. 2, pp. 68-70, Feb. 2001.

[2] Y. Cheng, P. Chen, W. Hong, T. Djerafi, and K. Wu, "Substrate-Integrated-Waveguide beamforming networks and multibeam antenna arrays for low-cost satellite and mobile systems," in IEEE Antennas and Propagation Magazine, vol.53, no.6, pp.18-30, Dec. 2011.

[3] P.-S. Kildal, E. Alfonso, A. Valero-Nogueira, and E. Rajo-Iglesias, "Local metamaterial-based waveguides in gaps between parallel metal plates," in IEEE Antennas Wireless Propag. Lett., vol. 8, pp. 84-87, 2009.

[4] P.-S. Kildal, A. Zaman, E. Rajo-Iglesias, E. Alfonso, and A. Valero-Nogueira, "Design and experimental verification of ridge gap waveguide in bed of nails for parallel-plate mode suppression," in IET Microwaves, Antennas Propagat., vol. 5, no. 3, pp. 262-270, Feb. 2011.

[5] P.-S. Kildal, "Three metamaterial-based gap waveguides between parallel metal plates for mm/submm waves," in *European Conference Antennas Propagat 2009 (EuCAP)*, Mar. 2009, pp. 28-32.

[6] E. Rajo-Iglesias, A. Zaman, and P.-S. Kildal, "Parallel plate cavity mode suppression in microstrip circuit packages using a lid of nails," in IEEE Microw. Wireless Compon. Lett., vol. 20, no. 1, pp. 31-33, Jan. 2010.

[7] H. Kirino, K. Ogawa, "A 76 GHz multi-layered phased array antenna using a non-metal contact metamaterial waveguide," in IEEE Trans. Antennas Prop., vol.60, no.2, pp.840-853, Feb. 2012.

[8] P.-S. Kildal, "Aperture efficiency and line feed phase center of parabolic cylindrical reflector antenna," in IEEE Trans. Antennas Prop., vol.32, no.6, pp. 553- 561, Jun 1984.

[9] P-S. Kildal, "Radiation characteristics of the EISCAT VHF parabolic cylinder antenna", IEEE Trans. Antennas Propagat., Vol. AP-32, No. 6, pp. 541-552, June 1984.

[10] M. Denstedt, T. Östling, J. Yang, P.-S. Kildal, "Tripling Bandwidth of Hat Feed by Genetic Algorithm Optimization", IEEE AP-S 2007 in Hawai, 10-15 June 2007.