Substrate Integrated Horn Antennas with Improved Aperture Efficiency

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I. Abstract

The tapered aperture distribution of the substrate integrated horn antenna always limits its aperture efficiency and widens the antenna beam width. Therefore, the integrated H-plane horn has rarely been considered for the applications where fan-beam types of radiation pattern are required. Here, the amplitude distribution of the integrated horn aperture has been improved to be almost uniform by the three methods of applying hard boundary conditions to the lateral walls of the horn. Among these three methods, air-filled integrated horn in which the internal substrate is removed by keeping a thickness of the dielectric on the walls shows wider improvement over the bandwidth**.**

II. Introduction

Recently the H-plane horn antennas integrated with substrates have got considerable attention because of their simplicity and ease of integration with other circuits. To improve this antenna performance, lots of work have been accomplished to improve the performance of the substrate integrated horn [1]-[5]. Here, three designs of the simple integrated horns are given in which the tapered amplitude distribution of the aperture in the simple horn is enhanced to the uniform distribution by modifying the boundary conditions of the lateral walls of the horn.

III. Aperture Improved Integrated Horn Designs and Comparisons

The optimum design for a waveguide which is integrated inside a substrate by via posts have been formulated and refined in many research works. In a simple look, it is just like a rectangular waveguide filled with dielectric; however, since two rows of metallic vias in the substrate serve as the narrow E-plane metal plates of the waveguide, some regulations have to be considered to keep the radiation loss low, and the SIW can be modelled by a conventional rectangular waveguide.

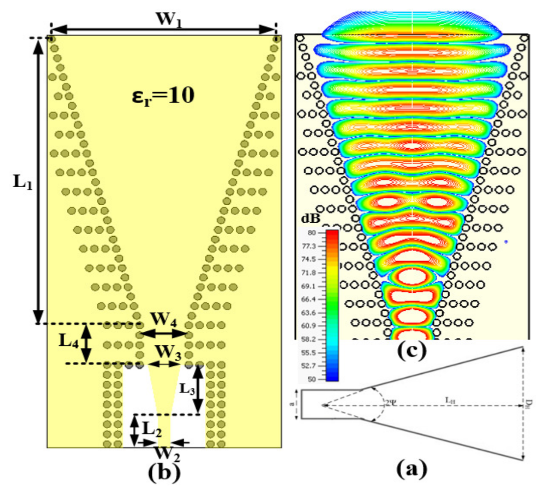

Fig. 1. (a) Basic geometry and parameters of H-plane horn (b) geometry of simple substrate integrated H-plane horn antenna (c) electric field distribution inside designed simple substrate integrated H-plane horn.

Accordingly, the diameter of metallic posts (d) and their spacing (p) should follow these limitations:

$$d < \lambda_g/5\ ,\ \ p < 2d \qquad (1)$$

where λ_g is the guided wavelength for the dominant mode in SIW. By flaring the lateral walls of the substrate integrated waveguide, integrated H-plane horn antenna can be achieved. The essential parameter the of H-plane horn antenna such as flare angle, aperture width, and horn length are all designed by following optimum design considerations given in [6] in order to reach high aperture efficiency and the antenna gain in which the optimum directivity occurs when the following relation between the horn length (L_1) and aperture width (W_1) is satisfied:

$$W_1 \cong \sqrt{3\lambda_g L_1}\ . \qquad (2)$$

A horn with the length of $10\lambda_g$ integrated into RO6010 with a dielectric constant of 10.2 and a thickness of 1.27 mm is shown in Fig. 1. In order for the horn to achieve lowest half power beam width, the flare angle has to be between 30 and 40 degrees according to curves illustrated in [6]. The horn is excited by 50-ohm microstrip line which is feeding the SIW with a tapered

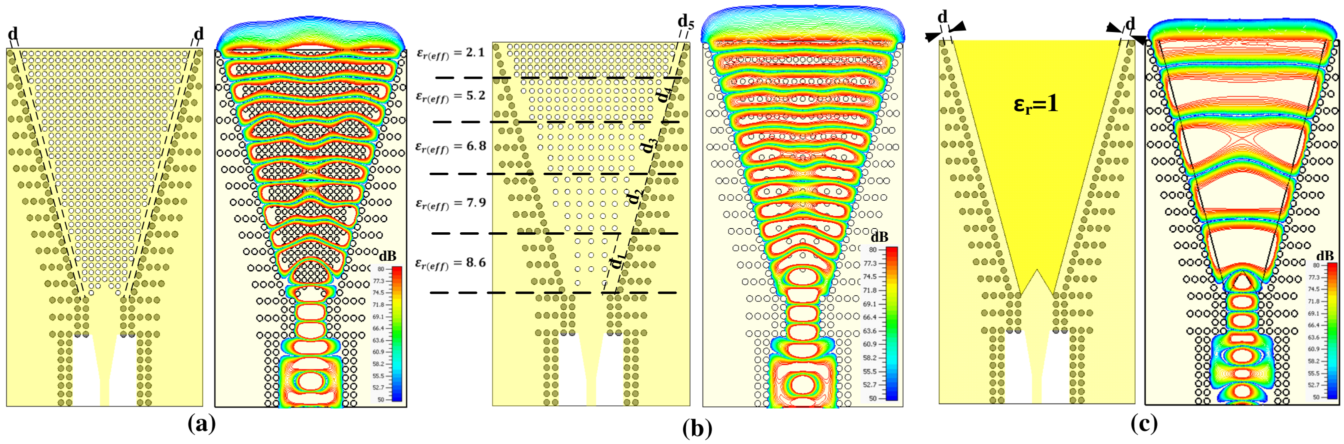

Fig. 2. Substrate integrated hard horn antennas and electric field distribution at the hard frequency (a) Perforated (b) 5-step perforated (c) air-filled

transition. The electric field distribution of the horn aperture indicates an entirely tapered amplitude distribution, as the boundary condition of the lateral PEC walls nullifies the field intensity close to the wall regions which limits the antenna aperture efficiency. This efficiency would not be improved even by widening the horn aperture. Therefore, the boundary condition of the lateral walls at the horn aperture has to be modified to intensify the field distribution close the aperture walls.

It is shown in [7] that air-filled horn antenna with longitudinal corrugations filled with a dielectric material with the relative permittivity of ε_r can realize hard boundary conditions when the depth of corrugations is:

$$d = {\lambda_0}/{4\sqrt{\varepsilon_r - 1}}. \tag{3}$$

For dielectric-filled horns like substrate integrated H-plane horn, inside of the horn has to have lower permittivity than areas close to the wall to achieve this boundary condition. The important factor that makes this condition at desired frequency is the thickness of high dielectric constant on the horn walls which could be determined by the following relation:

$$d = {\lambda_0}/{4\sqrt{\varepsilon_{r1} - \varepsilon_{r2}}} \tag{4}$$

where ε_{r1} is higher dielectric constant with the thickness of d backed by wall conductors, and ε_{r2} is the lower dielectric constant inside area of the horn. In order to realize the dielectric constant diversity inside substrate integrated horn, which is entirely fabricated with a single substrate, the perforation procedure has to be applied to the substrate inside the horn. In the perforated substrate, if the hole diameter and spacing remain very less than half-wavelength, the quasi-static effective permittivity of the perforated area can be determined using the volume average method [8] summarized hereinafter:

$$\alpha = \frac{\pi}{2\sqrt{3}}\left(\frac{d_{per}}{p_{per}}\right) \tag{5}$$

$$\varepsilon_{eff} = \varepsilon_r(1-\alpha) + \alpha \tag{6}$$

where d_{per} is the diameter of perforated holes, p_{per} spacing between the holes, and ε_r is the dielectric constant of the perforated substrate.

In Fig. 2(a), the integrated horn antenna with the perforated substrate is shown in which the effective permittivity of the perforated region is reduced to 2.1 by air-hole perforation with the diameter of 0.6 mm. The thickness of d with a dielectric constant of 10.2 is remained on the lateral walls to realize the hard conditions. As seen from the electric field distribution, perforating the horn substrate while having a thickness of high dielectric constant on the walls improves the aperture distribution of the horn.

Alternatively, instead of single step perforation, five-step perforations are applied to the same horn in Fig. 2(b). All of the steps are with the same via diameter, but with different spacing. Therefore, various effective permittivities are achieved which need different thicknesses of dielectric on the wall that can be calculated with the following relation:

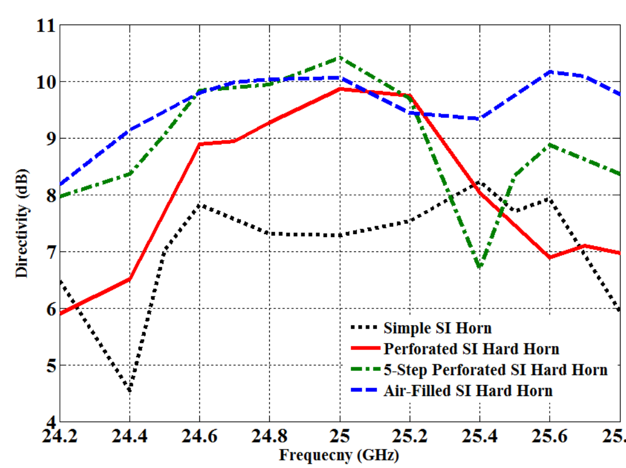

Fig. 3. Directivity comparison between simple integrated horn and perforated and air-filled hard horns.

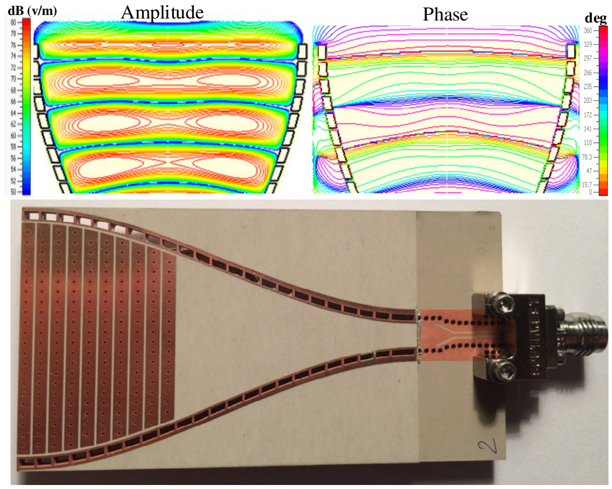

Fig. 4. The fabricated prototype of air-filled hard horn with amplitude and phase distribution of the aperture.

$$d_n = \lambda_0 \Big/ 4\sqrt{\varepsilon_r - \varepsilon_{rn(eff)}} \qquad (7)$$

where $\varepsilon_{rn(eff)}$ is effective permittivity of the nth step of the perforation and d_n is the required thickness of high dielectric constant for the nth perforated region. In the integrated horn of Fig. 2(b) the effective permittivity of the horn interior dielectric starts from 8.6 and end reaches to 2.1 with 5 steps perforation. Therefore, at the frequency of hard condition, almost uniform electric field distribution of the horn aperture is achieved. Applying five steps of perforation to the integrated horn instead of single step of Fig. 1 (a) has simplified the antenna geometry because of reducing the number of air-holes.

The hard boundary condition can also be realized by depleting the horn interior and filling it with air while keeping a thickness of dielectric on the walls (d) extracted from (3). For the substrate integrated horn shown in Fig. 2 (c) the uniform distribution of the aperture is obtained by cutting the horn inside substrate to have the relative permittivity of air inside and thickness of high dielectric constant on the walls. In Fig. 3, the directivity of the integrated hard horns are compared with the simple horn given in Fig. 1. As seen from this comparison, applying hard boundary condition of the lateral walls of the integrated H-plane horn has improved the antenna directivity more 2dB at 25 GHz, which is the center frequency of the hard condition, by unifying amplitude attribution of the aperture. Comparing the three integrated hard horns of Fig. 2, the single step perforated horn shows narrower bandwidth than 5-step perforated and air-filled hard horn, and it shows better improvement around center design frequency. However, air-filled horn demonstrates better hard frequency band comparing with two other perforated hard horns. In addition, air-filled horn demands less accuracy in the fabrication process than the perforated ones. Therefore, this horn is selected to be fabricated

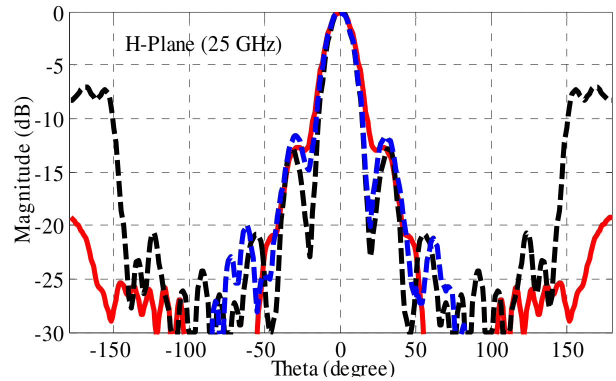

Fig. 5. Simulated and measured radiation patterns of the air-filled substrate integrated hard horn (solid lines, simulation; dashed black lines, simulation without soft surfaces; dashed blue lines, measurement).

in order to evaluate its performance. The difference between the perforated and air-filled hard horns is that the air-filled horn has to be covered with other grounded layers after the dielectric inside the horn is removed.

IV. Fabricated Prototype

The fabricated prototype of an integrated air-filled hard horn antenna is given in Fig. 4, which is accomplished by multi-layer PCB technology. Details of this design are given in [9]. The horn is designed for the center frequency of 25 GHz with hard lateral walls at this frequency. At this design, the hard walls of the horn are profiled to correct the aperture phase in order to reach uniform phase distribution besides uniform amplitude of the hard condition. The air cut area of the horn substrate is covered with two other grounded substrates which also equipped with strip-via array functioning as soft surfaces around the horn to suppress an aperture radiating wave to contribute antenna back radiations. The antenna is fed by conductor-backed coplanar waveguide (CBCPW) transmission line on the intermediate substrate and excited by end launch connector. The measured and simulated H-plane radiation pattern of the fabricate horn is shown in Fig. 5 at the hard frequency in which a narrow beam width with almost -13 dB side lobe levels are achieved because of the uniformity of phase and amplitude distribution of the aperture.

V. Conclusion

Three designs of substrate integrated horn antenna have been introduced with unified amplitude distribution of the aperture. Comparing the three designs has shown that the air-filled substrate integrated horn in which the hard boundary condition is realized by cutting the inside substrate and keeping a thickness of high dielectric constant on the walls demonstrates wider bandwidth of the improvement. A prototype of the air-filled integrated horn has shown with profiled hard walls, which provided the antenna with the uniform aperture phase accompanying uniform amplitude of the hard conditions.

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