Broadband Half Mode Substrate Integrated Waveguide H-plane Horn Antenna

Saeed Fakhte[1*] , Mohammad Hossein Asouri[1]
Department of Electrical and Computer Engineering, Qom University of Technology, Qom, Iran.
Email: fakhte@qut.ac.ir (Corresponding author)

Received: 18 June 2022 Revised: 1 July 2022 Accepted: 19 August 2022

ABSTRACT:
A compact, wideband, low cost, high radiation efficiency and planar half mode substrate integrated waveguide (HMSIW) horn antenna is proposed in this work. For the first time, HMSIW is used to design a horn antenna. By using HMSIW waveguide structure instead of Substrate Integrated Waveguide (SIW), the impedance bandwidth of antenna is increased significantly. The use of this waveguide structure in the design of the horn and its feeding system has increased the impedance bandwidth of the antenna. In fact, leaking the electromagnetic waves gradually along the horn increases the bandwidth of antenna. By applying the design equations of the H-plane horn antenna and half mode substrate integrated waveguide, the initial dimensions of the antenna have been obtained, then the best possible solution has been extracted by parametric study and optimization. Simulation results exhibit an impedance bandwidth of 50% from 24GHz to 40GHz. Also, the proposed design shows a gain between 7dB and 10 dB together with radiation efficiency higher than 95% over the frequency band of 25 to 35GHz. The innovation of this work is in providing a new horn structure based on HMSIW with wide impedance bandwidth. In the previously presented works, which are mainly based on SIW, the antenna suffers from a narrow impedance bandwidth.

KEYWORDS: HMSIW, Horn Antenna, Millimeter Wave.

1. INTRODUCTION

The substrate integrated waveguide H-plane sectorial horn antenna is recently introduced as a good candidate for rectangular waveguide horn antenna in millimeter wave region[1-6]. This structure can be easily integrated with the feed network and is a proper substitute to feed surface wave antennas [7-10].

Most reported SIW horn antennas have been suffered from narrow bandwidth which make them unsuitable for wideband applications [11]. In order to solve this problem, Ridge Substrate Integrated Waveguide (RSIW) horn antenna has been proposed in [12] to provide wide bandwidth at the cost of complex fabrication process. Also, techniques for enhancing the antenna gain have been proposed, such as dielectric loading of SIW horn antenna [13]. Note that in all of the aforementioned structures, the horn and SIW are integrated on a single substrate.

Various methods have been reported to increase the bandwidth of SIW horn antennas, including loading a dielectric slab with gradually decreasing dielectric constants [14], employing an arc-shaped copper taper printed on the extended dielectric slab and a three-step ridged SIW transition [15], introducing a pair of bowl-shaped reflectors in SIW [16], drilling air vias in half-open horn to smooth transition from half-open horn to free space [17], using periodic parallel strips on the top and bottom planes of the dielectric horn [18], and by reducing the effective dielectric constant by including an air layer between the top and bottom surfaces of SIW [19].

In [20], a half mode substrate integrated waveguide (HMSIW) H-plane horn antenna with a dielectric load has been introduced. The disadvantage of this structure is its narrow impedance bandwidth [21]. In [22], a leaky-wave antenna array based on half-mode substrate integrated waveguide (HMSIW) structure is proposed. This array has the beam scanning from -40° to 30° and compared to this work, which has a fixed beam, it is not suitable for fixed beam applications. A compact omnidirectional antenna on a cylindrical substrate was introduced [23]. This gives an impedance bandwidth of 0.95%, which is much smaller than the one proposed in this paper. In [24], the beam steering capability is introduced thanks to the use of varactor diodes in HMSIW horn antenna. The impedance bandwidth of this antenna cannot compete with the impedance bandwidth presented in our work.

Paper type: Research paper
DOI: 10.30486/mjee.2023.1970195.0
How to cite this paper: S. Fakhte and M. H. Asouri, **"Broadband Half Mode Substrate Integrated Waveguide H-plane Horn Antenna"**, *Majlesi Journal of Electrical Engineering*, Vol. 17, No. 2, pp. 23-28, 2023.

In this letter, a broadband half mode substrate integrated waveguide (HMSIW) H-plane sectorial horn antenna is proposed. Most leaky wave antennas are easily impedance matched. Typically, bandwidths are in the range of 15–30% but they can be higher [25],[26]. It is shown here that the proposed antenna is a leaky-wave antenna [27,28]. Consequently, its impedance bandwidth is widened.

While maintaining the advantageous characteristics of SIW H-plane sectorial horn antenna, the HMSIW horn antenna is more broadband and has the same fabrication cost compared with the SIW horn antenna.

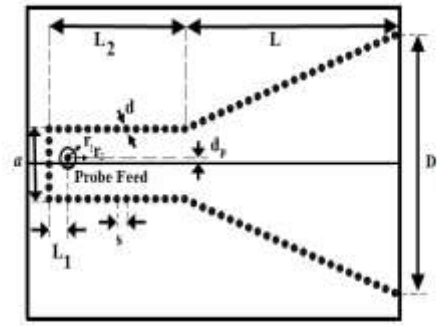
First, the structure of the antenna and its design procedure are described in detail. Then, simulation results are presented and discussed; finally, the paper is followed by a conclusion. The HMSIW horn antenna is designed for frequency range of 24-35 GHz. Simulation results illustrate that proposed antenna's VSWR is below 2 and good gain and high radiation efficiency are achieved.

2. ANTENNA DESIGN

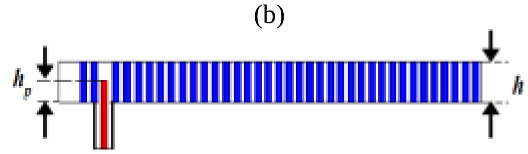
Fig. 1 shows the geometry of the proposed antenna. The HMSIW and horn structures made of two rows of copper-plated vias of diameter *d*, integrated on a dielectric substrate made of low loss material (RT Duroid 5880 of permittivity $\varepsilon_r = 2.2$, loss tangent 0.0009 and thickness $h = 2.54mm$) with its bottom side and half of top side are copper-plated. Therefore, the antenna structure is compact and easy to fabricate. The parameters $L_1, L_2, L, D, r_1, r_2, h_p$ and d_p as shown in Table 1 denote the probe relative position on HMSIW end, HMSIW length, horn axial length, horn aperture size, coaxial probe core radius, coaxial probe shield radius, probe height and probe relative position on top plate, respectively. The HMSIW's effective width is $a/2$ and the two neighboring vias are separated by S. In an HMSIW, only the quasi-$TE_{p-0.5,0}$ $(p=1,2,3,...)$ modes can propagate and the fundamental mode in HMSIW is similar to half of the dominant TE_{10} mode in SIW [7]. A comprehensive design guideline for the HMSIW has been presented in [7].The HMSIW's effective width is calculated by the cutoff frequency, f_c, using

$$f_{c,TE_{0.5,0}} = \frac{c}{4\sqrt{\varepsilon_r}\, w_{eff,HMSIW}} \tag{1}$$

(a)

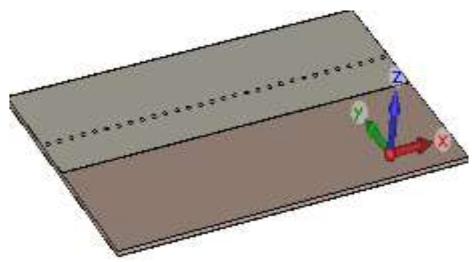


(b)

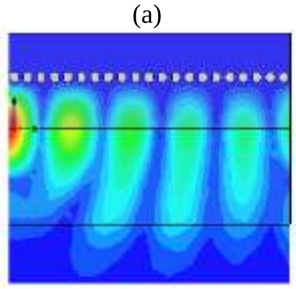


(c)

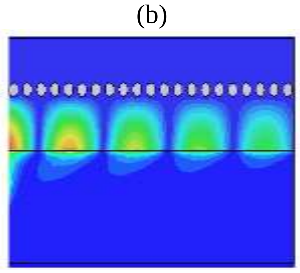
Fig. 1. (a) 3D view of the configuration of an HMSIW-horn antenna fed by a coaxial probe. (b) Top view of the configuration of the HMSIW-horn antenna. (c) Side view of the configuration of the antenna.



(a)



(b)



(c)

Fig. 2. (a) Configuration of an HMSIW (b) Electric field distribution of the qusi-$TE_{0.5,0}$ mode in the H-plane for a/2h=1.06 (c) and for a/2h=10.6.

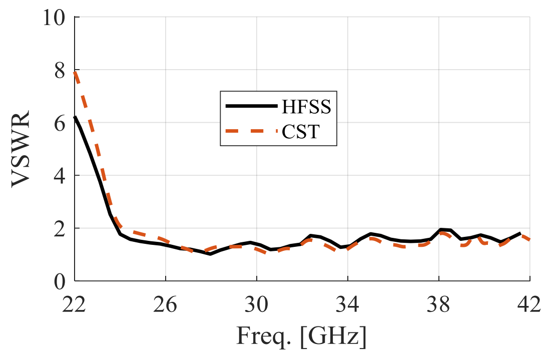


Fig. 3. Simulated VSWR of proposed antenna with two different solvers.

Where, c is the speed of light in vacuum, and ε_r is the dielectric constant of substrate. The vias diameter, d and separation, s in Fig. 1 are properly selected to minimize the RF power leakage. Subsequently, by substituting the known parameters, w_{eff}, d, s, substrate thickness, and ε_r in the following equations [27]:

$$w_{eff,SIW} = (2w) - 1.08\frac{d^2}{s} + 0.1\frac{d^2}{2w} \tag{1}$$

$$w_{eff,HMSIW} = w'_{eff,HMSIW} + \Delta w \tag{2}$$

$$\frac{\Delta w}{h} = (0.05 + \frac{0.3}{\varepsilon_r}) \times \ln(0.79\frac{w'^2_{eff,HMSIW}}{h^3} + \frac{104 w'_{eff,HMSIW} - 261}{h^2} + \frac{38}{h} + 2.77) \tag{3}$$

The only unknown parameter, i.e., the HMSIW physical width is calculated. Also, the frequency range for the single mode operation can be calculated by the calculation of the first higher order quasi- $TE_{1.5,0}$ mode cutoff frequency.

$$f_{c,TE_{1.5,0}} = \frac{3c}{4\sqrt{\varepsilon_r} w_{eff,HMSIW}} \tag{5}$$

Note that the HMSIW physical width, w, is chosen such that the $TE_{0.5,0}$ mode can be supported within the operating bandwidth of 19-56 GHz.

According to the analysis presented in [27], the thickness h of the waveguide should be small enough, but no special formula is provided for it. As a rough approximation, the thickness of the substrate can be considered to be about 0.1 of the width of the waveguide. By adjusting this parameter, the amount of wave leakage along the waveguide can be adjusted.

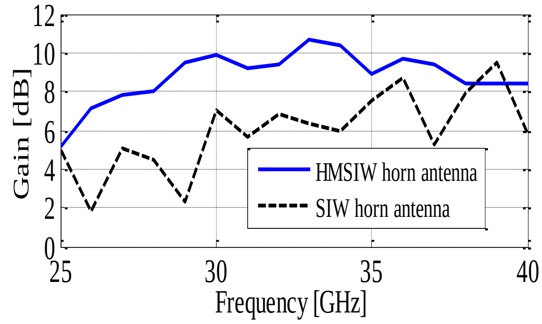


Fig. 4. Simulated gain for the HMSIW and SIW horn antennas.

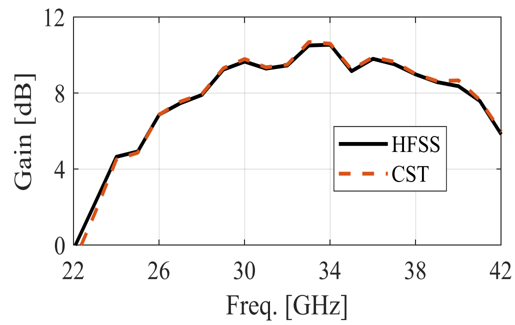
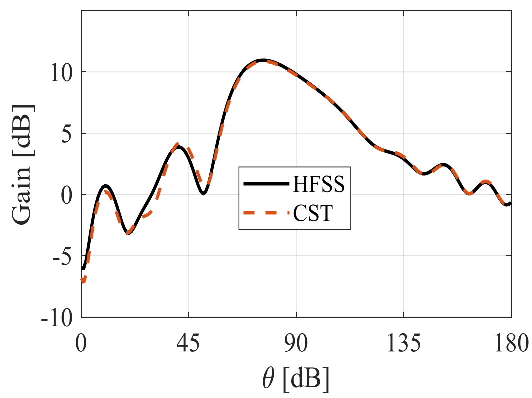
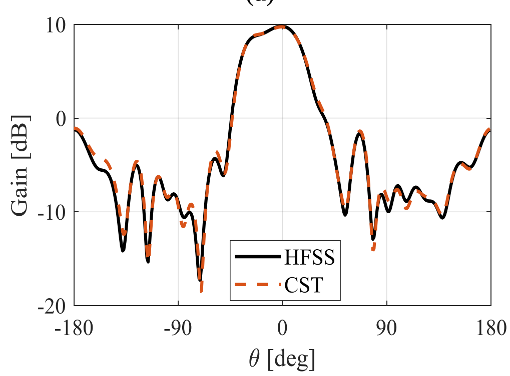


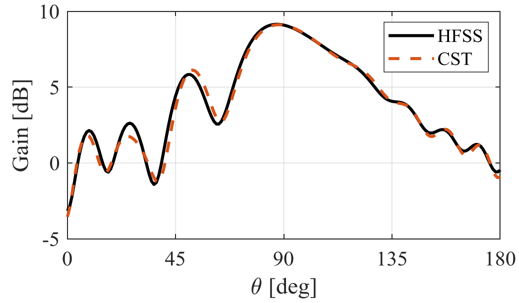
Fig. 5. Comparison between gains obtained from two different numerical methods.



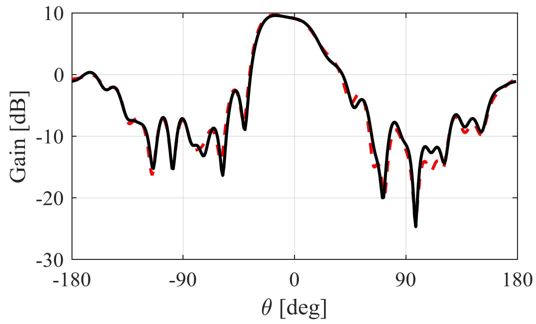
(a)



(b)



(c)



(d)

Fig. 6. Simulated antenna radiation pattern (gain) of proposed antenna, (a) E-plane at 30 GHz, (b) H-plane at 30 GHz, (c) E-plane at 35 GHz, (d) H-plane at 35 GHz.

The H-plane horn dimensions are calculated based on design guidelines mentioned in [28] for the equivalent SIW horn antenna which has a top side metallic layer width twice that of HMSIW.

The configuration of an HMSIW is shown in Fig. 2(a), which is half of an SIW. One side wall of the HMSIW is composed of a linear array of metallic vias and the other side is open. Due to the large ratio of the waveguide width to height, the open side is equivalent to a magnetic wall. In a HMSIW structure, since the width to height ratio is large, power leakage from magnetic wall is negligible (see Fig. 2(c)). In our design in order to maintain satisfactory gain, the aperture size must be wide enough. As a result, the substrate thickness should be as thick as possible, which violates the condition of large ratio of width to height and the electromagnetic wave is not confined completely in HMSIW. Consequently, the open side can radiate and the antenna acts like a leaky wave antenna.

The same rows of vias with respect to XZ symmetry plane are formed to guide the fringing fields into the horn aperture (see Fig. 1(b)). As a result, the antenna gain will be increased. Note that to eliminate the higher order modes propagation in HMSIW, the thickness of substrate should be restricted.

3. NUMERICAL INVESTIGATION

The proposed configuration was optimized using CST in terms of impedance bandwidth and gain. In order to optimize these parameters, the effect of different parameters on gain and s11 was checked by parametric study and the best answer was selected. Then, by using the CST software optimizer, the best possible solution has been selected around the range of the previous values.

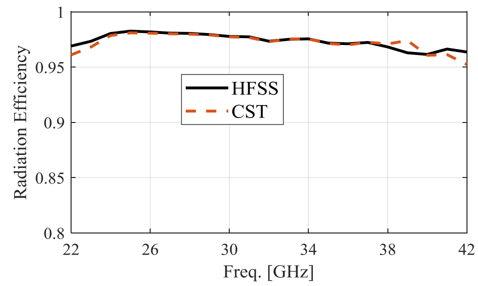


Fig. 7. The simulated radiation efficiency of the proposed antenna.

Fig. 3 shows the simulated VSWR of the final optimized HMSIW horn antenna and its equivalent SIW horn antenna. Observe that, HMSIW horn antenna is matched over about 17.5 GHz frequency bandwidth of 24-40 GHz. Also observe that the SIW base horn antenna impedance bandwidth is very narrow compared to HMSIW base antenna. The gain versus frequency response for HMSIW and SIW horn antennas are drawn in Fig. 4. Observe that the HMSIW horn antenna gain is above $6\,dB$ over the whole frequency band of interest, with a peak of $10.5\,dB$ at $f = 33.5GHz$. The proposed antenna gain is higher than that of SIW which is due to the higher radiation aperture of HMSIW base antenna.

Table 1. Optimized parameters of the proposed antenna..

Parameter	*L1*	*dp*	*hp*	*h*	*a*	*d*
Value(mm)	*2*	*0*	*1.5*	*2.54*	*2.54*	*0.6*
Parameter	*s*	*L2*	*D*	*L*	r_1	r_2
Value(mm)	*0.9*	*12.6*	*20*	*20*	*0.3*	*0.7*

The comparison of antenna characteristics (namely VSWR, and gain) of the HMSIW and SIW horn antennas indicates that the HMSIW horn has more desirable characteristics with the same fabrication cost.

A comparison between the gains obtained from the simulation with CST and HFSS software can be seen in Fig. 5. A good agreement between the results of the two software has been obtained.

The radiation patterns obtained at two frequency points, i.e., 30GHz, and 35GHz, are illustrated in Figs. 6(a) and 6(b) in both E- and H-planes, respectively. Observe that the E-plane patterns have relatively high side lobes owing to the thickness of substrate at *h=2.54mm*. Moreover, the radiation patterns in E-plane have some deformation that makes them non-symmetric around the broadside direction ($\theta = 90^\circ, \varphi = 0^\circ$), which is more pronounced at 30 GHz. This is expected due to the non-perfect metallization on the top side of structure in comparison with the perfect metallization on bottom side. As shown in Fig. 7, the proposed antenna achieves more than 95% antenna efficiency within the operation band.

4. CONCLUSION

An HMSIW H-plane sectorial horn antenna for millimeter wave applications was designed to provide wide impedance bandwidth. While maintaining the same fabrication cost of SIW ones, the present design of an HMSIW horn antenna has a wider impedance bandwidth and better gain. The simulated 2:1 VSWR bandwidth of this design is over 50%. Its radiation efficiency is also better than 95%. This antenna has a directional radiation pattern in the frequency range of 22 to 40 GHz. The wide bandwidth of this antenna is obtained due to the gradual leakage of the electromagnetic wave along the HMSIW horn. The results obtained from simulation with CST have been confirmed by simulation in HFSS.

REFERENCES

[1] Kanth, V. Krushna, and S. Raghavan. "**EM design and analysis of frequency selective surface based on substrate-integrated waveguide technology for airborne radome application.**" *IEEE Transactions on Microwave Theory and Techniques* 67, No. 5, pp. 1727-1739, 2019.

[2] Qin, Chong, Fu-Chang Chen, and Kai-Ran Xiang. "**A 5× 8 Butler matrix based on substrate integrated waveguide technology for millimeter-wave multibeam application.**" *IEEE Antennas and Wireless Propagation Letters* 20, No. 7, pp. 1292-1296, 2021.

[3] Varikuntla, Kushna Kanth, and Raghavan Singara Velu. "**Design and development of angularly stable and polarisation rotating FSS radome based on substrate-integrated waveguide technology.**" *IET Microwaves, Antennas & Propagation* 13, No. 4, pp. 478-484, 2019.

[4] Zhang, Yi-Xuan, Yong-Chang Jiao, and Li Zhang. "**Wideband inhomogeneous-polarizer loaded circularly polarized SIW horn antenna for broadband millimeter-wave applications**." *IEEE Antennas and Wireless Propagation Letters* 18, No. 7, pp. 1448-1452, 2019.

[5] Jamshidi-Zarmehri, Hojjat, and Mohammad H. Neshati. "**Design and development of high-gain SIW H-plane horn antenna loaded with waveguide, dipole array, and reflector nails using thin substrate.**" *IEEE transactions on antennas and propagation* 67, No. 4, pp. 2813-2818, 2019.

[6] Chen, Yaling, Long Zhang, Yejun He, Chunxu Mao, Sai-Wai Wong, Wenting Li, Peng Chu, and Steven Gao. "**Broadband high-gain SIW horn antenna loaded with tapered multistrip transition and dielectric slab for mm-Wave application**." *IEEE Transactions on Antennas and Propagation* 70, No. 7, pp. 5947-5952, 2022.

[7] Zhang, Yin, Jing-Ya Deng, Dongquan Sun, Jia-Yuan Yin, and Li-Xin Guo. "**Compact slow-wave SIW H-plane horn antenna with increased gain for vehicular millimeter wave communication**." *IEEE Transactions on Vehicular Technology* 70, No. 7, pp. 7289-7293, 2021.

[8] Kumar, Abhay, and Shweta Srivastava. "**Four element three-dimensional SIW horn antenna array for high-frequency applications**." *International Journal of RF and Microwave Computer‐Aided Engineering* 31, No. 6, e22660, 2021.

[9] Zechmeister, Jaroslav, Jaroslav Lacik, and Petr Kadlec. "**The design of pixelated SIW horn antennas with nearly equal beamwidths using binary ink stamp optimization**." *IEEE Access* 9, pp. 122216-122227, 2021.

[10] Farashahi, Mohammadreza, Ehsan Zareian-Jahromi, and Raheleh Basiri. "**A compact wideband circularly polarized SIW horn antenna for K band applications.**" *AEU-International Journal of Electronics and Communications* 99, pp. 376-383, 2019.

[11] H. Wang, D. –G. Fang, B. Zhang, and W. –Q. Che, "**Dielectric loaded substrate integrated waveguide (SIW) H-plane horn antennas**," *IEEE Trans. Antennas Propag*., Vol. 58, No. 3, pp. 640-647, March. 2010.

[12] A. R. Mallahzadeh, and S. Esfandiarpour, "**Wideband H-plane horn antenna based on ridge substrate integrated waveguide (RSIW),**" *IEEE Antenna Wireless Propag. Lett*. Vol. 11, pp. 85-88, 2012.

[13] R. Kazemi, A. E. Fathy, and R. A. Sadeghzadeh, "**Dielectric rod antenna array with substrate integrated waveguide planar feed network for wideband applications**," *IEEE Trans. Antennas Propag*., Vol. 60, No. 3, pp. 1312-1319, March. 2012.

[14] Cai, Yang, Zuping Qian, Wenquan Cao, Yingsong Zhang, Jun Jin, Liu Yang, and Nan Jing. "**Compact wideband SIW horn antenna fed by elevated-CPW structure.**" *IEEE Transactions on Antennas and Propagation* 63, No. 10, pp. 4551-4557, 2015.

[15] Zhao, Yun, Zhongxiang Shen, and Wen Wu. "**Wideband and low-profile H-plane ridged SIW horn antenna mounted on a large conducting plane**." *IEEE Transactions on Antennas and Propagation* 62, No. 11, pp. 5895-5900, 2014.

[16] Ge, Lei, Kwai Man Luk, and Shichang Chen. "**360° beam-steering reconfigurable wideband substrate integrated waveguide horn antenna**." *IEEE transactions on Antennas and Propagation* 64, No. 12 , pp. 5005-5011, 2016.

[17] Cai, Yang, Yingsong Zhang, Liu Yang, Yufan Cao, and Zuping Qian. "**A low-profile wideband surface-mountable substrate-integrated waveguide horn antenna.**" *IEEE Antennas and Wireless Propagation Letters* 16, pp. 2730-2733, 2017.

[18] Wang, Lei, Maria Garcia-Vigueras, Marcos Alvarez-Folgueiras, and Juan R. Mosig. "**Wideband H-plane dielectric horn antenna.**" *IET Microwaves, Antennas & Propagation* 11, No. 12, pp. 1695-1701, 2017.

[19] Ghosh, Anik, and Kaushik Mandal "**High gain and wideband substrate integrated waveguide-based H-plane horn antenna**." *AEU-International Journal of Electronics and Communications* 105, pp. 85-91, 2019.

[20] Razavi, Seyed Ali, and Mohammad H. Neshati. "**Low profile H-plane horn antenna based on half mode substrate integrated waveguide technique.**" In *20th Iranian Conference on Electrical Engineering (ICEE2012)*, pp. 1351-1354. IEEE, 2012.

[21] Razavi Parizi, Seyed Ali, and Mohammad Hassan Neshati. "**A Dielectric Loaded HMSIW H-Plane Horn Antenna.**" In *Progree In Electromagnetic Research-PIER*. 2012.

[22] Geng, Yunjie, Junhong Wang, Yujian Li, Zheng Li, Meie Chen, and Zhan Zhang. "**A Ka-band leaky-wave antenna array with stable gains based on HMSIW structure.**" *IEEE Antennas and Wireless Propagation Letters* 21, No. 8, pp. 1597-1601, 2022.

[23] Bhowmik, Wriddhi, and Shweta Srivastava. "**Design of compact omnidirectional substrate integrated waveguide exponentially tapered multiple H-plane horn antenna**." *AEU-International Journal of Electronics and Communications* 108, pp. 29-35, 2019.

[24] René-Loxq, David, Olivier Lafond, Mohamed Himdi, Langis Roy, and Farhan Ghaffar. "**New reconfigurable HMSIW associated to horn antenna**." In *2022 16th European Conference on Antennas and Propagation (EuCAP)*, pp. 1-4. IEEE, 2022.

[25] W. Hong, et al., "**Broadband Tapered Microstrip Leaky Wave Antenna**," *IEEE Trans. Antennas. Propag*, Vol. 51, pp. 1922–1928, 2003.

[26] W. L. Stutzman, G. A. Thiele, *Antenna Theory and Design,* John Wiley & Sons Inc., 2012.

[27] Q. H. Lai, C. Fumeaux, W. Hong, and R. Vahldieck, "**Characterization of the propagation properties of the half-mode substrate integrated waveguide**," IEEE Trans. Microw. Theory Tech., Vol. 57, No. 8, pp. 1996–2004, Aug. 2009.

[28] Stutzman, Warren L., and Gary A. Thiele. *Antenna theory and design*. John Wiley & Sons, 2012.