PERFORMANCE COMPARISON OF PYRAMIDAL HORNS LOADED WITH METAL BAFFLE OR WITH METAMATERIAL

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Abstract—Two recent methods that have been reported in the literature to improve the performance of pyramidal horns are metal baffle loading and the use of epsilon-near-zero metamaterial. In this paper, a comparative study of the two methods is undertaken for the case of Ku- and X-band horns. In addition to the simulation study, a C-band metal baffle loaded horn was fabricated and rigorously characterized. It emerges from the study that E-plane metal baffle loading improves the radiation characteristics of the horn much better than the loading by metamaterial. Furthermore, the baffle loading nearly retains the construction simplicity, weight and cost of the normal pyramidal horn.

1. INTRODUCTION

The pyramidal horn is widely used as a standard gain horn, as a feed for reflector and as an element in phased array antennas due to its such salient features as high gain, moderate bandwidth, construction simplicity, good power handling capability and low fabrication cost [1–4]. To make the pyramidal horn more compact, several approaches

that include lens-correction [5–7] and dielectric loading [8, 9] have been considered. However, these compact horns, apart from being in general heavy and expensive, present a high dielectric loss. In view of this, more recently, loading by metal baffle [10–12] and metamaterial [13–16] have been considered.

The idea of metal baffle loading to improve the performance of the pyramidal horn appears to have been first introduced in [10], and subsequently investigated more thoroughly in [11]. It is shown in [11] that the performance of a short X-band pyramidal horn is substantially improved when it is loaded with a pair of planar E- and H-plane metal baffles. However the return loss of the horn thus loaded is high, and also the gain- versus-frequency plot exhibits multiple null regions. Thus the useable bandwidth is reduced. In [12], triangular E-plane metal baffle loading approach has been proposed to overcome these shortcomings of the planar metal baffles-loaded horn. The horn proposed in [12] exhibits monotonically increasing gain behavior, a salient feature of the horn antenna [2, 17, 18], a return loss of better than 15 dB over the entire X-band, and improved cross-polarization level.

According to [19], the first paper on metamaterial-loaded horn appeared in 1941. In that first paper (which, incidentally, has not been explicitly cited in [19]; however it is believed to be [20], available in [1]), and also in [5], the gain of a short horn was shown to become comparable to that of optimum horn over a narrow bandwidth, when a layer of metal plates (metamaterial) was attached in front of the horn. The modern terminology for this type of metamaterial is epsilon-near-zero (ENZ) metamaterial or wire-medium [14]. After a lull, there has now been a revival of interest on the topic, with a number of articles having recently appeared on ENZ metamaterial-loaded pyramidal horn antennas [13–16]. In two of these efforts [13, 14], the metamaterial is inserted inside the normal pyramidal horn. While this approach does shorten the horn, the bandwidth obtained is very narrow, matching is relatively poor, and complexity is substantial.
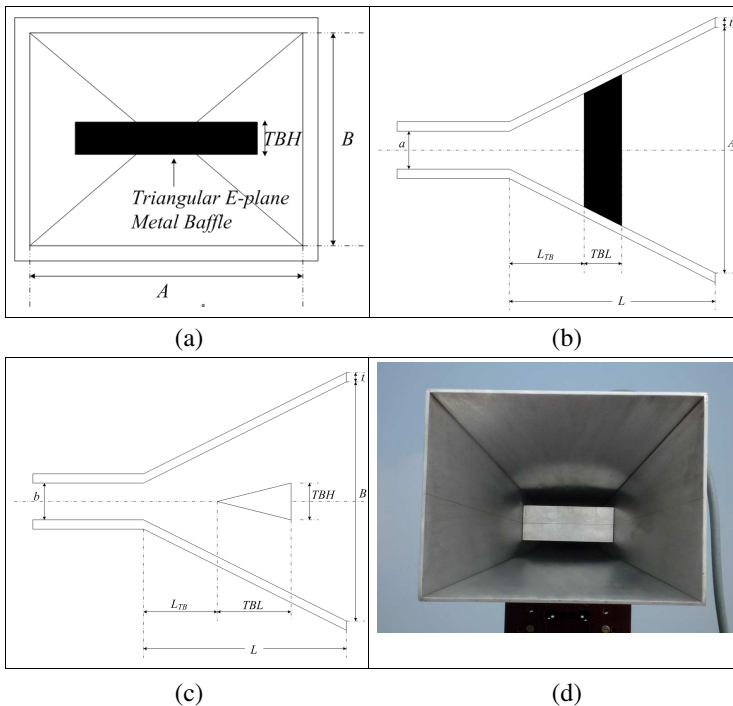
In this paper, a simulation- and measurement-based study is undertaken on the performances of the triangular E-plane metal baffle and ENZ metamaterial loaded normal pyramidal horns. The results show that the use of triangular E-plane metal baffle loading outperforms the metamaterial-loaded short horns with respect to gain, aperture efficiency, radiation patterns, matching and bandwidth. At the same time, the resulting horn nearly preserves all the desired features of normal pyramidal horn such as the normal gain behavior, bandwidth, simplicity and fabrication cost. It thus appears that the triangular E-plane metal baffle is an alternative to the currently reported ENZ metamaterial loading techniques for

performance improvement of pyramidal horns. To validate the proposed technique, a metal baffle loaded C-band pyramidal horn is fabricated and rigorously measured.

The paper is organized as follows: Section 2 presents the geometry of the triangular E-plane metal baffle-loaded horn. The extensive simulation results of the baffle-loaded horn and metamaterial-loaded pyramidal horns are compared in Section 3 while Section 4 compares the simulation and measurement results of a C-band unloaded and metal baffle loaded horn. Section 5 discusses the results and the conclusion drawn in Section 6.

2. GEOMETRY OF THE TRIANGULAR E-PLANE METAL BAFFLE LOADED PYRAMIDAL HORN

Figures 1(a) to (e) show the geometry and the physical outlook of the triangular E-plane metal baffle loaded pyramidal horn. The performance of the horn depends, apart from the horn dimensions, on the baffle height (T_{BH}), length (T_{BL}) and position (L_{TB}). All these dimensions need to be optimized by using an appropriate simulation tool.

(a)   (b)
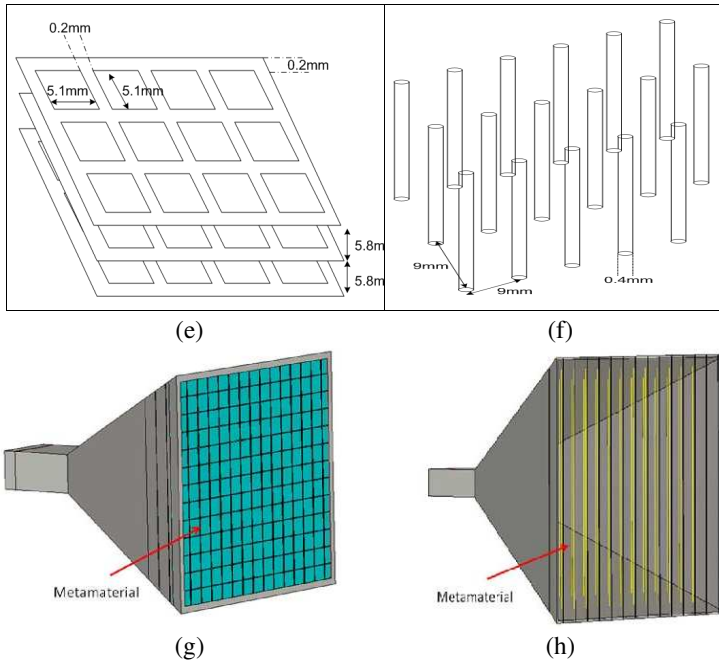
(c)   (d)

Figure 1. The geometry of the proposed triangular shaped *E*-plane metal baffle-loaded pyramidal horn: (a) Front view, (b) *H*-plane cross-section view, (c) *E*-plane cross-section view, (d) Photograph of an experimental C-band baffle-loaded pyramidal horn, (e) Ku-band ENZ metamaterial lattice constant, (f) X-band ENZ metamaterial lattice constant, (g) simulation model of the Ku-band ENZ loaded horn, (h) simulation model of the X-band ENZ loaded horn.

An experimental C-band baffle-loaded horn is made by inserting a baffle into a C-band short pyramidal horn available in the lab (this horn had been used in [21]). Parametric studies were carried out on the axial location of the triangular *E*-plane metal baffle (L_{TB}) for chosen baffle height (T_{BH}) and given length (T_{BL}) of the short horns. The dimensions are given in Table 1.

The two epsilon-near-zero metamaterial-loaded short pyramidal horns considered in [13, 14] are chosen for the present simulation-based comparative study. For ready reference, the metamaterial lattice constants used in [13] and [14] are given in Fig. 1(e) and Fig. 1(f), respectively; more details can be found in these references. In both the cases, the metamaterial is placed inside the horn aperture; see Fig. 1(g) and Fig. 1(f). While the Ku-band ENZ metamaterial has a plasma frequency of 15.81 GHz with the corresponding epsilon values of 0 to 0.23 (from 15.81 GHz to 18 GHz), the X-band ENZ has a plasma

frequency of 9.3 GHz with the corresponding epsilon values of 0 to 0.44 (from 9.3 GHz to 12.4 GHz).

Table 1. Dimensions of the triangular E-plane metal baffle-loaded horns.

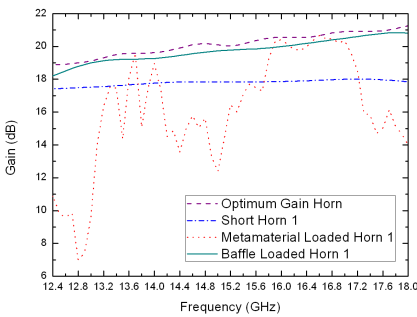| Label	Dimension in (mm)								
	A	B	a	b	L	L_{TB}	T_{BH}	T_{BL}	T
Baffle Loaded Horn 1 (Ku-band)	75.49	67.59	15.79	7.90	64.00	12.00	13.00	13.00	2.00
Baffle Loaded Horn 2 (X-band)	125.00	112.00	22.50	10.00	99.00	15.00	19.50	19.50	1.00
Baffle Loaded Horn 3 (C-band)	288.00	213.50	35.00	16.00	259.00	30.00	40.71	40.71	3.00

Figure 2. Simulated gains of the Ku-band Horns: Optimum gain horn, 44% Shorter Horn (short horn 1), metamaterial loaded short horn (Metamaterial loaded horn 1) and the proposed triangular E-plane metal baffle-loaded short horn (Baffle loaded horn 1).
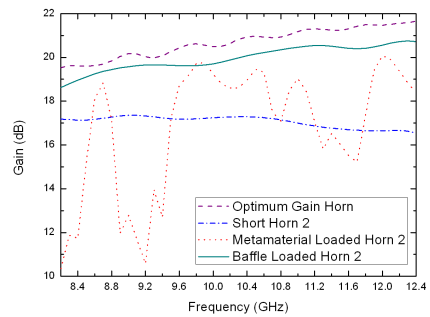

Figure 3. Simulated gains of the X-band Horns: Optimum gain horn, 48% Shorter Horn (short horn 2), metamaterial loaded short horn (Metamaterial loaded horn 2) and the proposed triangular E-plane metal baffle-loaded short horn (Baffle loaded horn 2).

3. SIMULATED RESULTS

Extensive simulation studies by using the commercial 3D electromagnetic simulation package CST Microwave Studio were undertaken to compare the performance of the triangular E-plane metal baffle-loaded horns with that of pyramidal horns loaded with metamaterial.

Figures 2 and 3 displayed the simulated gains in the Ku- and X-band of unloaded horns and horns loaded with triangular E-plane metal baffle and ENZ metamaterial. As could be seen, the baffle-loaded horns offer a gain improvement of about 3 dB through the bands while retaining the normal gain behavior of the optimum gain horns. On the other hand, the metamaterial-loaded horns offer similar gain improvement only over several narrow bands.

The aperture efficiency of the horns is compared in Figs. 4 and 5 for the Ku- and X-band horns respectively. Understandably, it is observed that the efficiency of the triangular E-plane metal baffle-loaded horns is better than the unloaded and metamaterial loaded horns throughout the full bands. Besides, the baffle-loaded horns offer comparable efficiencies as the unloaded optimum gain pyramidal horn at much shorter length.

As should be expected, the return loss of both the metamaterial- and metal baffle-loaded horns would be higher than that of the unloaded horns. This is seen in Figs. 6 and 7 for the Ku- and X-band horns respectively. However, the baffle-loaded horns perform much better than the metamaterial-loaded horns in respect of return loss too. As has been observed through simulation, the return loss of the baffle-loaded horn can be improved to better than 15 dB by further optimizing the tapered section of the baffle, but at the price of slightly lower gain.
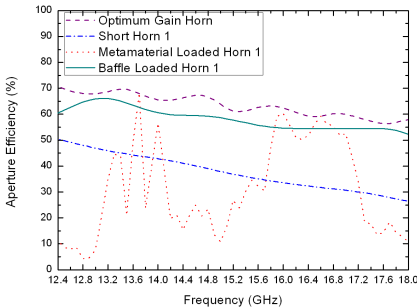

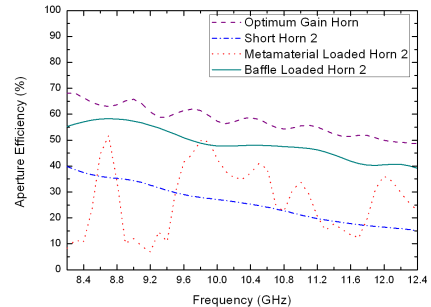**Figure 4.** Aperture efficiencies of the Ku-band horns.

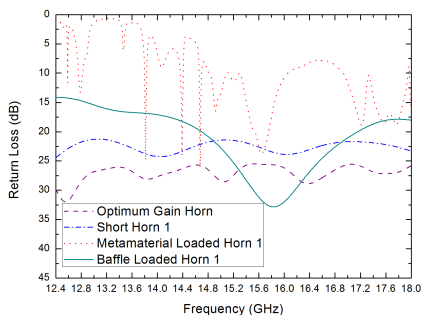**Figure 5.** Aperture efficiencies of the X-band horns.

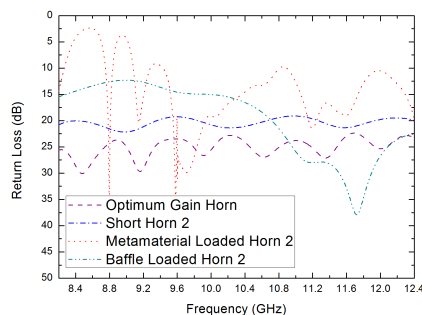**Figure 6.** Return loss of the Ku-band horns.

Figure 7. Return loss of the X-band horns.

The E- and H-plane radiation patterns of the different horns considered in the study are shown for the Ku- and X-band in Figs. 8 and 9 respectively. The patterns are shown at the band-edge, mid-band and resonant frequencies. As can be generally seen, the baffle-loaded horns offer much better E-plane patterns (with respect to directionality and sidelobes level) than the other horns. The H-plane patterns of baffle-loaded horns are broader than the optimum horns but narrower than the unloaded short horns.

4. EXPERIMENTAL SETUP AND MEASUREMENT RESULTS

The modified three antenna method [21] is applied to characterize the gain of the C-band unloaded and baffle-loaded short pyramidal horn. The measurement was conducted in SAMEER-Center for Electromagnetics, Chennai. The three horns comprised a commercial C-band standard gain horn as the reference antenna and two pyramidal horns, one of them with metal baffle-loading. The separation distance between the transmitting and receiving horns was 5 m and the horns were mounted at 2.5 m height. With this setup, power measurement was repeated ten times for the different combination of the horns. The 3σ measurement uncertainty level in the frequency band of 5.8 to 8.2 GHz is believed to be within ± 0.5 dB.

Figure 10 shows the measured and simulated gain of the unloaded- and proposed metal baffle-loaded horns. As seen from the figure, the gain of the pyramidal horn with metal baffled-loading was higher by 0.8 dB to 5.2 dB over the entire C-band frequencies. Also, the simulated and measured results are in good correlation. The respective aperture efficiency of the two horns is show in Fig. 11. As expected, the aperture efficiency of the proposed metal baffle-loaded horn is higher compared to that of the unloaded horn.
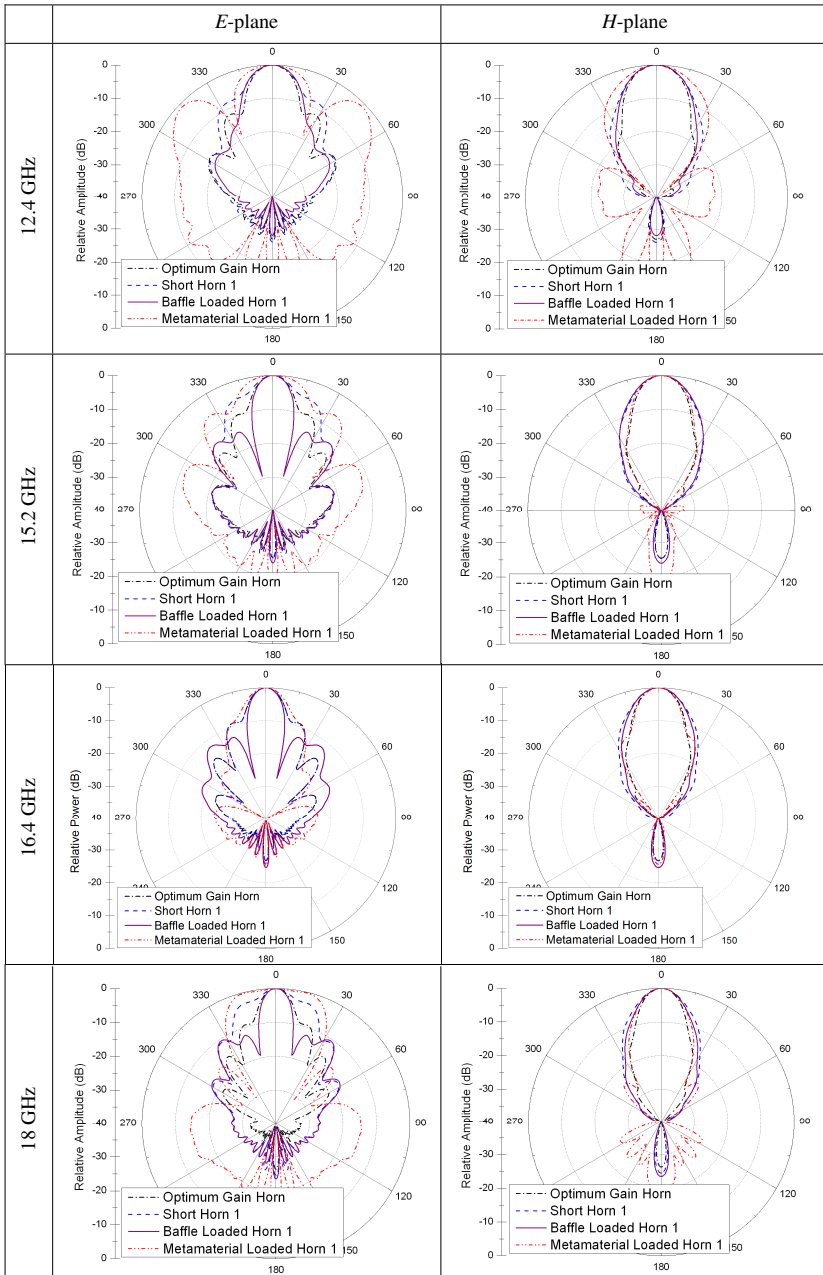
Figure 8. The principal *E*- and *H*-plane radiation patterns of the three horns at the band edges and center frequency of the Ku-band.
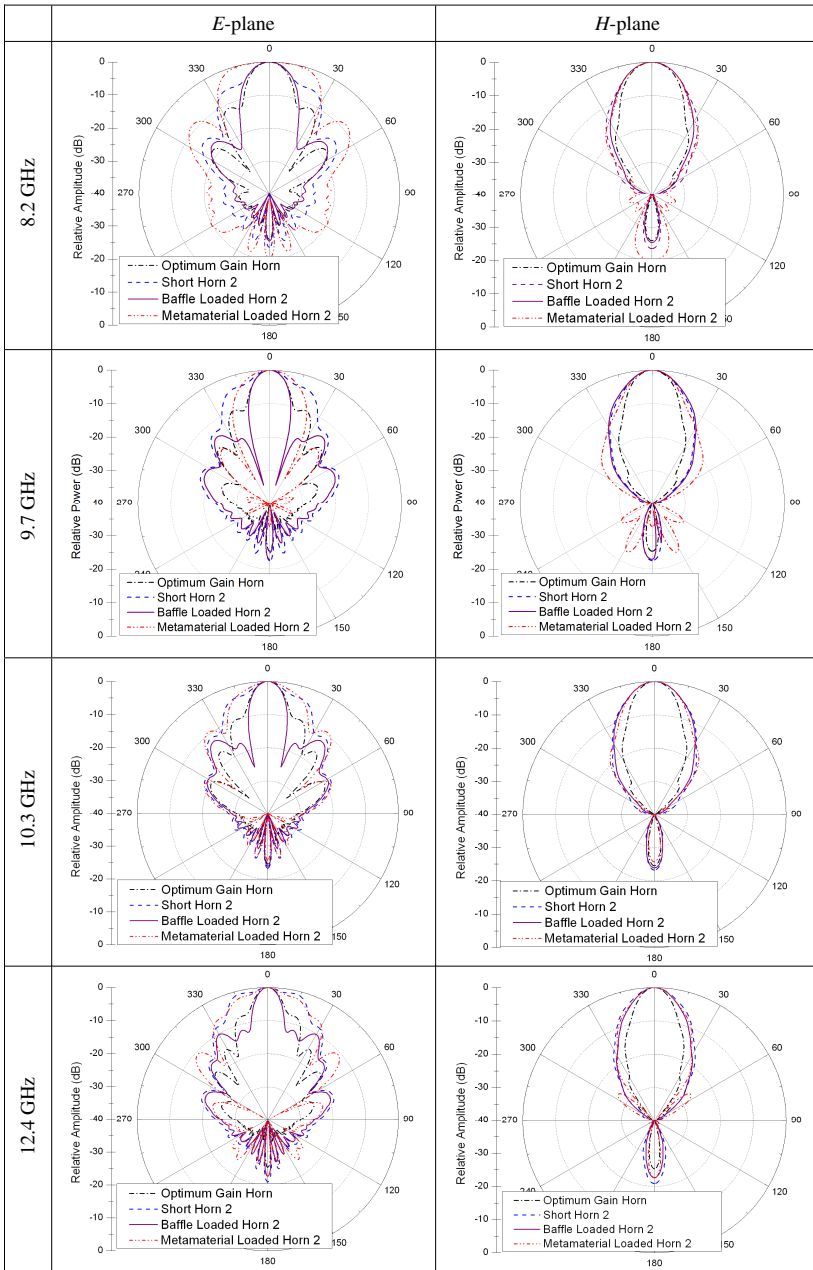
Figure 9. The principal *E*- and *H*-plane radiation patterns of the three horns at the band edges and center frequency of the X-band.

The return loss of the two horns is shown in Fig. 12. The mismatch between the measured and simulated results is believed to be due to the coaxial adaptor not being included in the simulation model. While considering the measured return loss of the unloaded (short horn 3) and metal baffle loaded horns, it is observed that the baffle loading marginally worsens the return loss of the unloaded horn. This finding is consistent with Figs. 6 and 7.

Figure 13 shows the measured and simulated E- and H-plane of the two horns. As observed from Fig. 13, baffle loading narrows the E-plane beamwidth and lowers the side-lobes level of the unloaded horn. Interestingly, the baffle loading is also seen to be useful in eliminating the E- and H-plane pattern squint of the unloaded horn at 8.2 GHz.
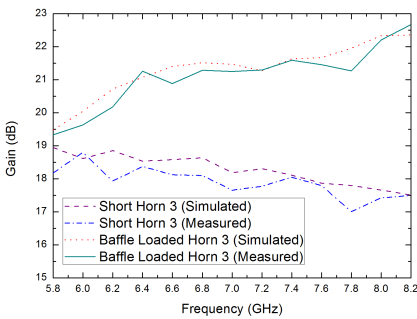

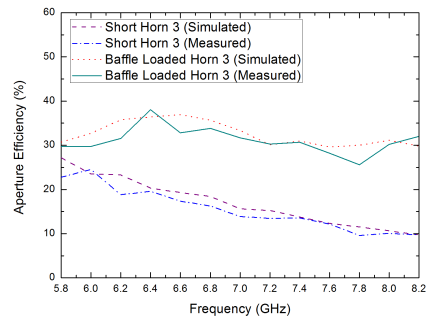**Figure 10.** Measured and simulated gains of the C-band horns.

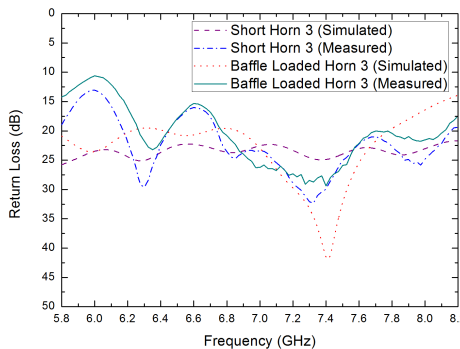**Figure 11.** Measured and simulated aperture efficiency of the C-band horns.

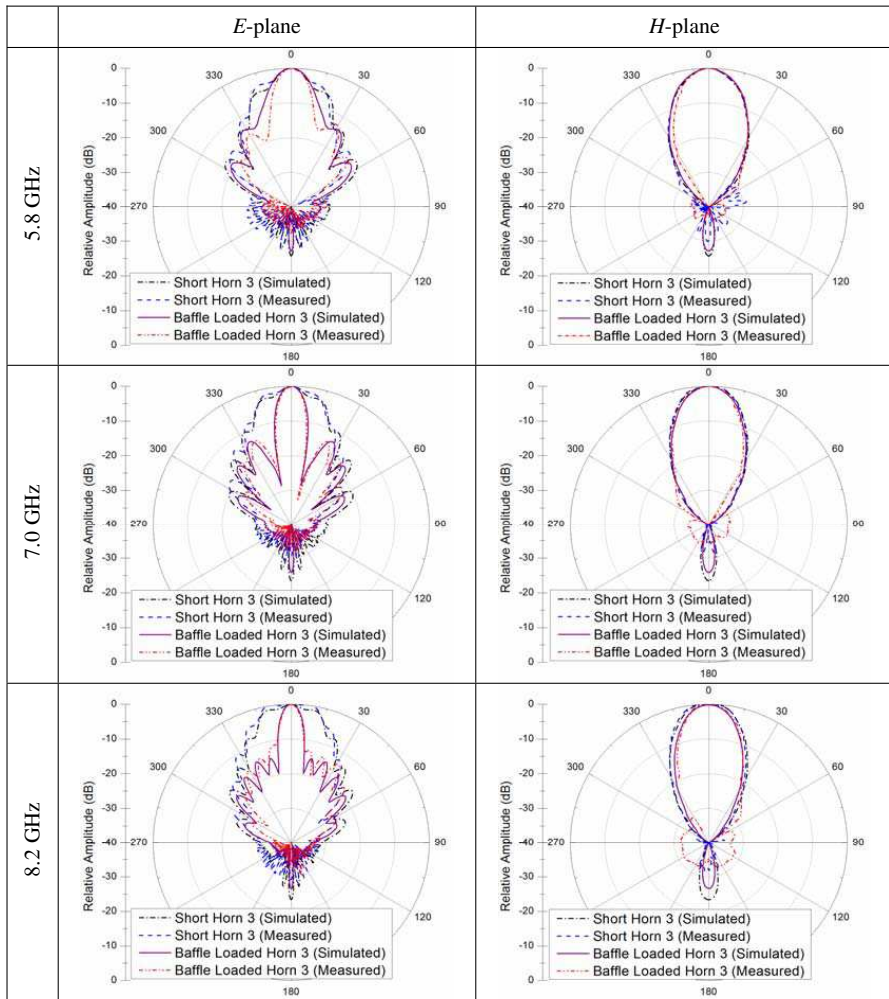**Figure 12.** Measured and simulated return loss of the C-band horns.

Figure 13. Measured and simulated E- and H-plane radiation pattern of the unloaded and baffle-loaded horns.

5. DISCUSSION

In an attempt to better understand the reasons for the above observations, Figure 14 shows the simulated electric field distributions in the E-plane (YZ-plane) and the H-plane (XZ-plane) at 10.3 GHz for the unloaded short horn and also for the horns loaded with triangular E-plane metal baffle and metamaterial. As seen, the E-plane wave fronts of the baffle-loaded horn are more uniform than those of the other horns. However, the same cannot be said of the H-
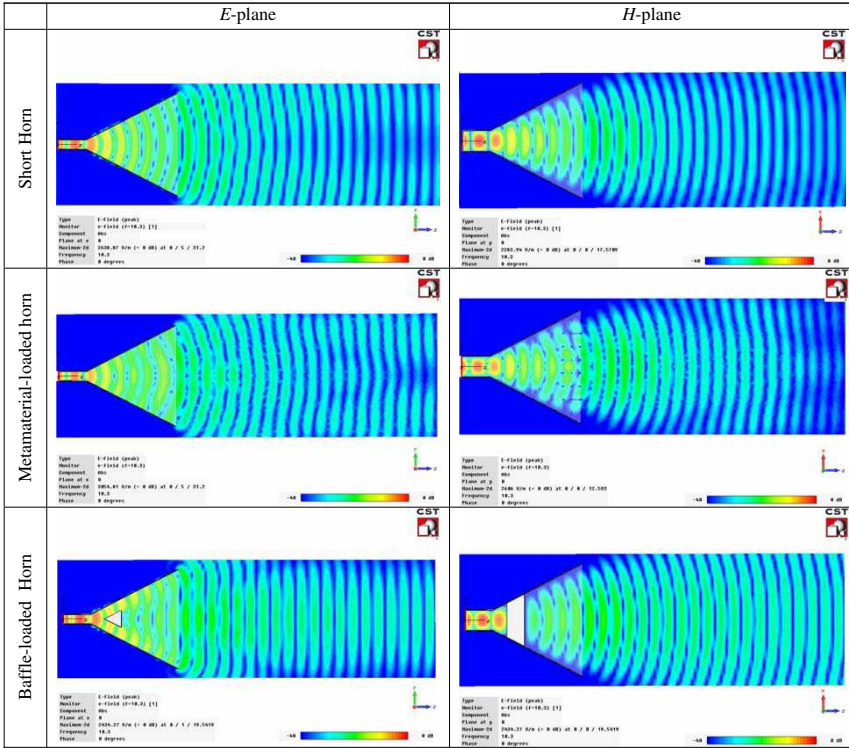
Figure 14. Electrical field distributions of the three horns at the center frequency (10.3 GHz) of X-band.

plane wave fronts. It may be deduced that loading by *H*-plane baffle will possibly result in more uniform wave fronts in that plane. An implication is that the *E*- and *H*-plane phase errors of the short horn can be corrected by using appropriate metal baffle loadings.

6. CONCLUSION

In this paper, a simulation-based comparative study was undertaken on the performance of X- and Ku-band pyramidal horns loaded with triangular *E*-plane metal baffle or with epsilon-near-zero metamaterial. In general, in both the bands (X- and Ku-band), the baffle-loaded horn was seen to offer better performance than the metamaterial-loaded horn. In addition to the simulation study, an *E*-plane metal baffle-loaded horn operating in C-band was fabricated and rigorously characterized to validate the simulation findings.

While the study does demonstrate that the proposed triangular

E-plane metal baffle loading technique is more effective to improve the performance of a short pyramidal horn compared to with ENZ metamaterial-loading, is it by no means to discourage the research on metamaterial, indeed it indirectly encourage to research on a better type of metamaterial to improve the horn performance. Surprisingly, the findings could be in line with [22] where the authors showed that the dielectric- and Frequency Selective Surface (FSS)-superstrates loading methods are more effective to improve the microstrip antenna directivity compared to double-negative (DNG) metamaterial. Also, the directivity improvement bandwidth of dielectric-superstrate is greater than FSS-superstrate microstrip antenna.

In short, from a practical point of view, the baffle-loading entails much lower fabrication complexity than the considered ENZ metamaterial loading, with corresponding cost implication. Moreover, the proposed technique offers better radiation characteristics compared to the considered metamaterial-loading. The proposed horn may be useful as a feed element in phased array system.

REFERENCES

1. Love, A. W., *Electromagnetic Horn Antennas*, IEEE Press, New York, 1976.

2. Stutzman, W. L. and G. A. Thiele, *Antenna Theory and Design*, 2nd edition, John Wiley & Sons, 1998.

3. Balanis, C. A., *Antenna Theory Analysis and Design*, 3rd edition, John Wiley & Sons, New Jersey, 2005.

4. Bird, T. S. and A. W. Love, "Horn antennas," *Antenna Engineering Handbook*, 4th edition, 14-1–14-74, J. Volakis (ed.), McGraw-Hill, 2007.

5. Kock, W. E., "Metal-lens antennas," *Proceedings of the IRE*, Vol. 34, 828–836, 1946.

6. Chatterjee, R., *Antenna Theory and Practice*, 2nd edition, New Age International, 1996.

7. Elliott, R. S., *Antenna Theory and Design*, Revised edition, John Wiley & Sons, 2003.

8. Lier, E. and R. Landes, "High gain linearly polarised dual band horn for multi-feed reflector antenna," *Electronics Letters*, Vol. 39, 1230–1232, 2003.

9. Tsandoulas, G. and W. Fitzgerald, "Aperture efficiency enhancement in dielectrically loaded horns," *IEEE Transactions on Antennas and Propagation*, Vol. 20, 69–74, 1972.

10. Risser, J. R., "Waveguide and horn feeds," *Microwave Antenna*

Theory and Design, 1st edition, S. Silver (ed.), 383, McGraw-Hill, 1949.

11. Koerner, M. A. and R. L. Rogers, "Gain enhancement of a pyramidal horn using *E*- and *H*-plane metal baffles," *IEEE Transactions on Antennas and Propagation*, Vol. 48, 529–538, 2000.

12. Tan, C. Y. and K. T. Selvan, "Performance improvement of pyramidal horn using triangular *E*-plane metal baffle," *3rd European Conference on Antennas and Propagation, 2009. EuCAP 2009*, 3034–3037, 2009.

13. Wu, Q., P. Pan, F.-Y. Meng, L.-W. Li, and J. Wu, "A novel flat lens horn antenna designed based on zero refraction principle of metamaterials," *Applied Physics A: Materials Science & Processing*, Vol. 87, No. 2, 151–156, May 2007.

14. Hrabar, S., D. Bonefacic, and D. Muha, "ENZ-based shortened horn antenna — An experimental study," *IEEE Antennas and Propagation Society International Symposium, 2008. AP-S 2008*, 1–4, 2008.

15. Hwang, R.-B., H.-W. Liu, and C.-Y. Chin, "A metamaterial-based *E*-plane horn antenna," *Progress In Electromagnetics Research*, Vol. 93, 275–289, 2009.

16. Xiao, Z. and H. Xu, "Low refractive metamaterials for gain enhancement of horn antenna," *Journal of Infrared, Millimeter and Terahertz Waves*, Vol. 30, 225–232, March 2009.

17. Selvan, K. T., "Derivation of a condition for the normal gain behavior of pyramidal horns," *IEEE Transactions on Antennas and Propagation*, Vol. 48, 1782–1784, 2000.

18. Tan, C. Y., K. T. Selvan, and Y. M. Koh, "Derivation of conditions for the normal gain behavior of conical horns," *International Journal of Antennas and Propagation*, Vol. 2007, 4, 2007.

19. Ramsay, J., "Highlights of antenna history," *IEEE Antennas and Propagation Society Newsletter*, Vol. 23, 7–20, 1981.

20. Rust, N. M., "The phase correction of horn radiators," *J. Inst. Elec. Eng.*, Vol. 93, 50–51, Mar–May 1946.

21. Selvan, K. T., "A modified three-antenna gain measurement method to simplify uncertainty estimation," *Progress In Electromagnetics Research*, Vol. 57, 197–208, 2006.

22. Mittra, R., Y. Li, and K. Yoo, "A comparative study of directivity enhancement of microstrip patch antennas with using three different superstrates," *Microwave and Optical Technology Letters*, Vol. 52, No. 2, 327–331, February 2010.