一般社団法人　電子情報通信学会
THE INSTITUTE OF ELECTRONICS,
INFORMATION AND COMMUNICATION ENGINEERS

信学技報
IEICE Technical Report
A・P2023-77(2023-09)

Effect of faceting on medium Gain homogeneous spherical lens

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Abstract The aperture efficiency of 28dBi-class single plastic spherical lenses fed by a scalar feed is limited to 75%. This results from the peculiar aperture distribution created by the lens-feed system. For switched beam applications a flat facet face can be cut facing the immobile feed. The facet size was investigated for common plastic relative permittivities 2.1 to 2.7 for a fixed sphere radius of 5 wavelengths illuminated by a 10dBi scalar feed across 24% bandwidth in a commercially available simulator. Peak aperture efficiencies above 90% were achieved without increasing the Gain ripple across the band.

Key words lens antenna, Q-band antenna, Non Terrestrial Network.

1. Introduction

Homogeneous spherical lens antennas having Gain between 26 to 30dBi are of interest for Q-band mechanically steered or switched beam aerial unit onboard antenna for Non-Terrestrial Networks [1]. Spherical homogeneous lenses were studied extensively 60 years ago [1], to the point where empirical equations describing the effects of lens ε_r on the aperture size diminution and lossiness of the plastic used were derived. These equations were combined and used to model spherical lenses made from readily available plastics in [2]. However, the relationship between the spherical lens and the presumably scalar feed, however, been complex as the near field interaction cannot be simply described by an empirical equation. The scalar feed to lens interaction can only be modelled by numerical simulation or if time and resources allow should be done by experimental trial and error [3]. Changing the scalar feed to change the illumination beam width modifies the aperture distribution of the homogeneous lens within limits. Or, conversely, for a set scalar feed exchanging one ε_r sphere for another will change the aperture illumination and thus the far field radiation pattern [3].

In a switched beam implementation the lens and feeds are immobile. Minor shaping of the sphere at the point closest to the feed gives a further degree of freedom, to change the illumination of the lens. Modified spherical lenses have been investigated in the past for different applications [4]. The most interesting of these was array thinning a microstrip line fed microstrip patch array for a munitions seeker head by augmenting each patch with a facetted spherical lens [5, 6]. Here facetted spherical lenses were tried at a larger radius of $5\lambda_0$, Figure 1.

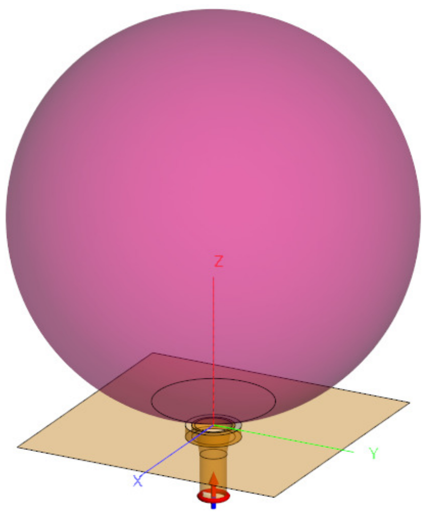

Figure 1: CAD of scalar feed fed faceted lens .

2. Classification of the scalar feed

Five different scalar feeds were trialed in prior work on $4\lambda_0$ radius lenses [3]. A sixth type which was neglected at the time due to time constraints is described in [7]. The 12GHz version of that antenna is given in Figure 2. Its performance fitted between that of the 3-ring choke and Cowan feeds in [3]. Here it was used in the centre of a 250mm square ground plane, Figure 1. The ground plane caused some minor ripple in the E-plane, but the E-H pattern equality was still reasonable across ±30°, Figure 3. Across 24% bandwidth the Directivity ranged from 10.15 to 10.95dBi, Figure 4.

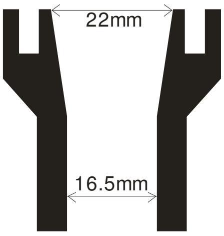

Figure 2: 12GHz version CSIRO scalar feed from [1].

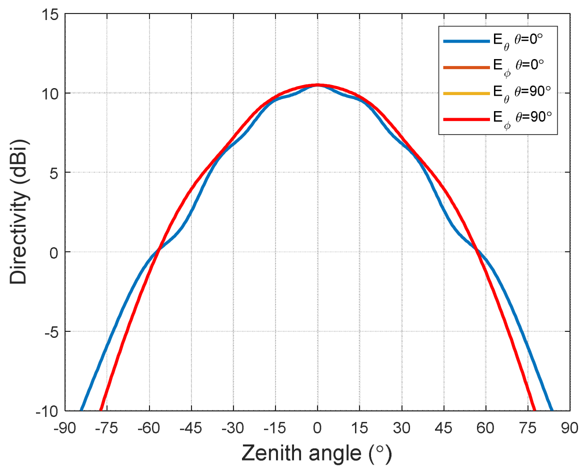

Figure 3: Far field radiation patterns of scalar feed; from FEKO™.

From the ε_r=2.1 to 2.5 focusing results in [3] it was expected that the edge of the spherical lens would be around 10mm above the scalar feed here. This places the illumination acceptance arc of the lens well within the near field of the feed, Figure 5. Note that the near field of this scalar feed is not rotationally symmetric. Any modification of the spherical lens surface will change the amplitude and phase distribution of the radio waves entering the lens, thus changing the illumination. Here a single facet was cut normal to the axis of the feed presenting it with a flat surface, Figures 1 and 6.

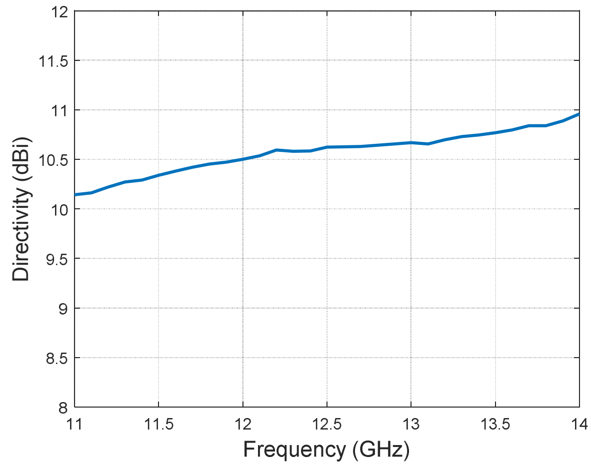

Figure 4: Far field radiation patterns of scalar feed; from FEKO™.

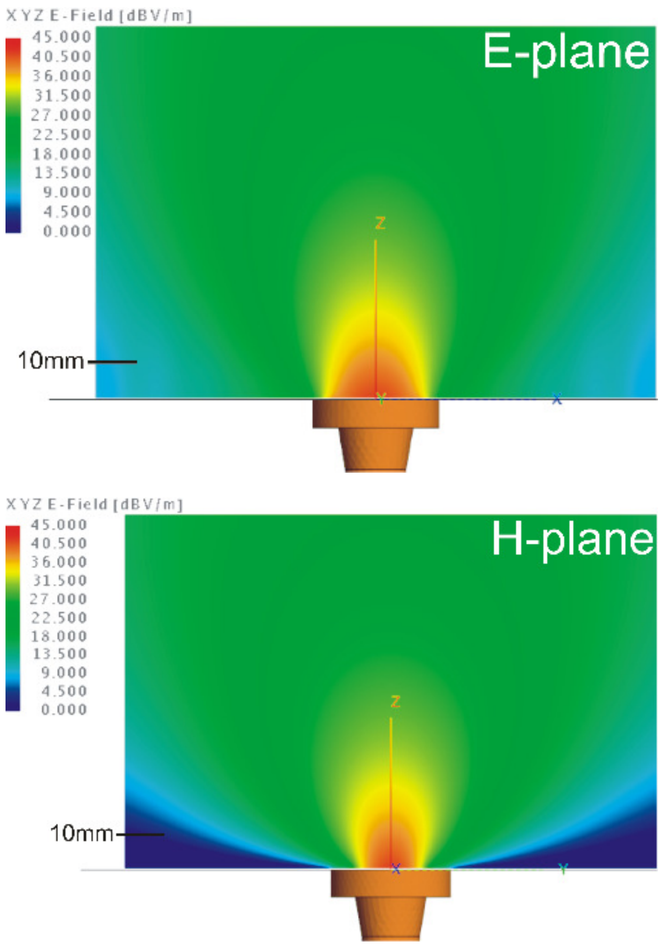

Figure 5: E_t near field radiation patterns of scalar feed; from FEKO™.

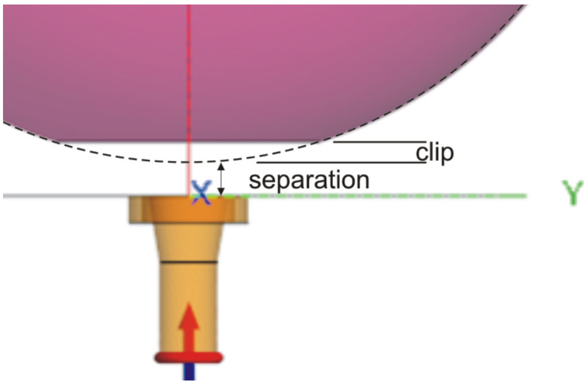

Figure 6: Diagram for faceting parametric study.

3. Faceting parametric study

A parametric study of the effects of lens separation from the scalar feed and depth (or clip) of the facet on lens Directivity was undertaken in Altair FEKO™ at 12GHz for lens ε_r of 2.1, 2.3, 2.4, 2.54, 2.7 and 2.9, thus covering most of the low loss plastics discussed in [2]. The Directivity results for all 6 ε_r are presented in the same format with lens surface to feed separation as the X-axis and facet “clip” height as the Y-axis, Figures 7 to 12. The Directivity results along the X-axis at clip=0mm are a repeat of the data in Figure 4 of [3]. Across ε_r=2.1 to 2.9, the separation giving the highest Directivity moved from 28.9mm to 2mm, in agreement with the theory discussed in [1]. These non-faceted peak Directivity results are the baseline for each ε_r spherical lens with any increase caused by faceting been an improvement as was found for all 6 ε_r studied.

4. Comparison of faceted lenses

Three sets of representative results were selected for examination across 24% bandwidth. As a shorthand the designs are labelled in the format of separation/clip. The S_{11} of the scalar feed was affected by presence of all the lenses with its smooth characteristic showing increased level and multiple resonances, Figures 13, 15 and 17. All 3 spherical lenses had Directivity oscillations across 11 to 14GHz, caused by multiple resonances in the interaction of direct optical ray-like radiation and the induced surface currents, Figure 14, 16 and 18. Both the ε_r=2.54 and 2.7 spherical lenses were in oscillation troughs at 12GHz, somewhat undermining the parametric study discussed above. In all cases, the optimal facetted lens gave higher Directivity than the spheres at 12GHz, and generally across the 24% bandwidth. As a further crude generalization, the higher Directivity faceted lenses had lesser amplitude Directivity oscillations.

For ε_r=2.1 both the spherical and 2 faceted lenses studied were more than $1\lambda_0$ away from the scalar feed. The level and trend of the S_{11} followed that of the feed by itself but having more than a dozen resonances caused by the lenses, Figure 13. Above 12.5GHz the feed failed to sufficiently illuminate the lenses with the consequence that the aperture efficiency decreased from around 80% at 12.5GHz to 60% at 14GHz. Above 11.5GHz the 32.3/7.7 facetted lens gave higher Directivity than the simple sphere with there been a 0.8dB advantage at 12.7GHz, Figure 14.

In contrast to the S_{11} for the ε_r=2.1 lenses, the S_{11} for the ε_r=2.54 lenses did not track that of the feed by itself, Figure 15. Having the spherical lens 5mm from the feed was apparently far too close for frequencies below 12.5GHz as the S_{11} was uniquely high compared to the other 3 designs studied for which S_{11}<-12dB, Figure 15. Also of note is that the resonances of each of the 4 lenses never aligned, showing the complexity and unpredictability of the lens – feed interaction. The same applies for the Directivity characteristics, Figure 16. Overall the 2 facetted lenses gave up to 0.5dB Directivity increase over the 14mm separation baseline spherical lens, with narrow band aperture efficiency peaks of 85%. Interestingly, the actual physical distance from the scalar feed to the nearest part of the lens were all around the 14 to 15mm mark for ε_r=2.54, which bares further investigation possibly with a time domain code.

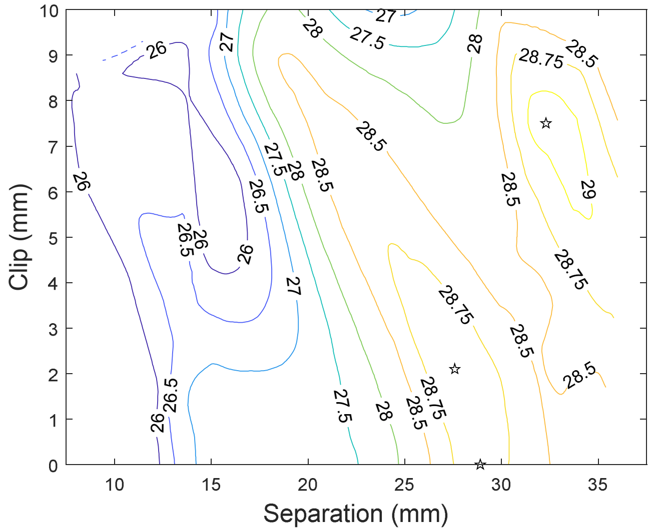

Figure 7: Peak Directivity for faceting parametric study with ε_r=2.1, from FEKO™.

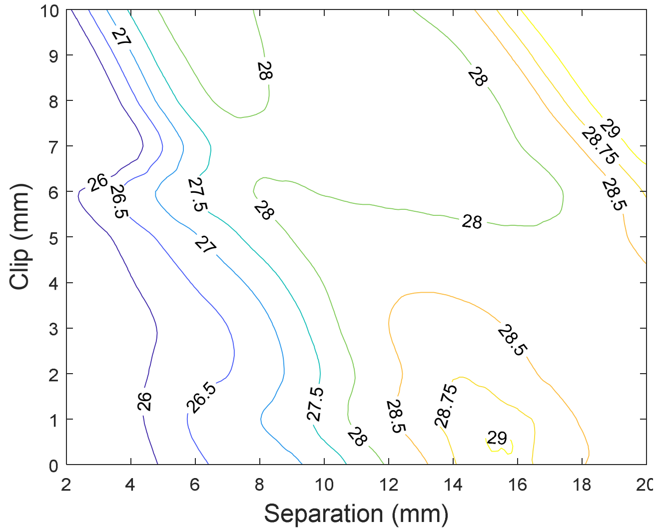

Figure 8: Peak Directivity for faceting parametric study with ε_r=2.3, from FEKO™.

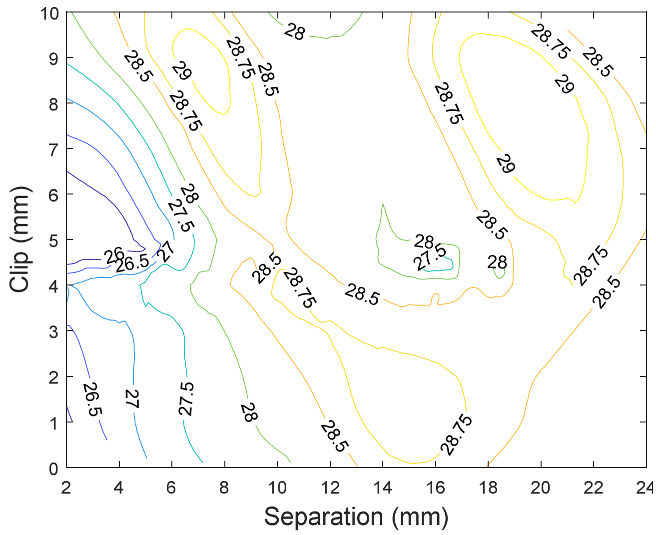

Figure 9: Peak Directivity for faceting parametric study with ε_r=2.4, from FEKO™.

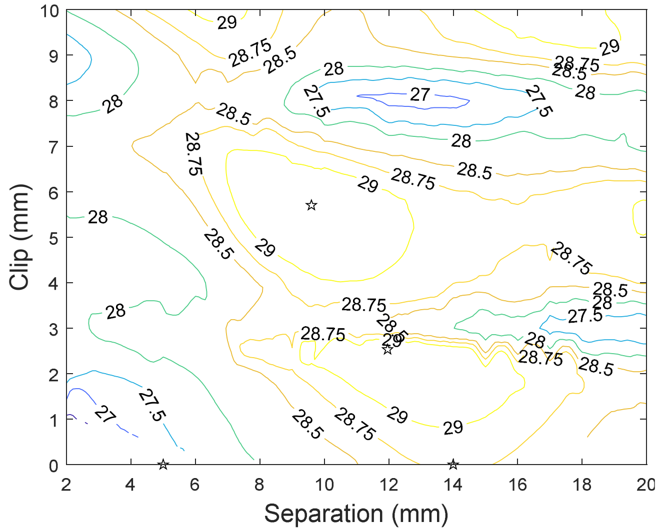

Figure 10: Peak Directivity for faceting parametric study with ε_r=2.54, from FEKO™.

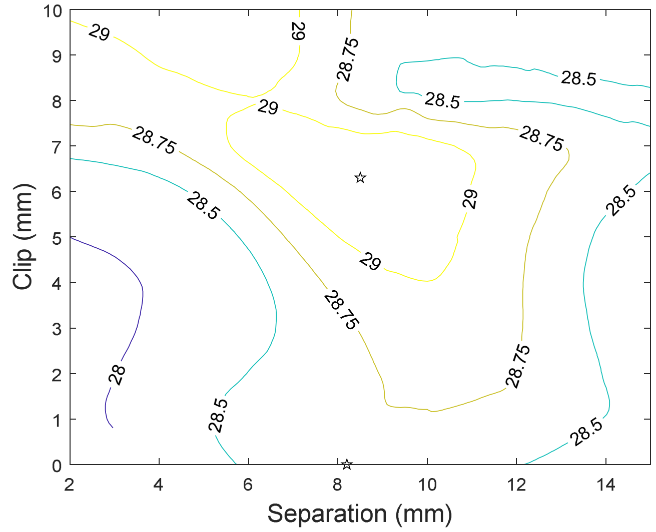

Figure 11: Peak Directivity for faceting parametric study with ε_r=2.7, from FEKO™..

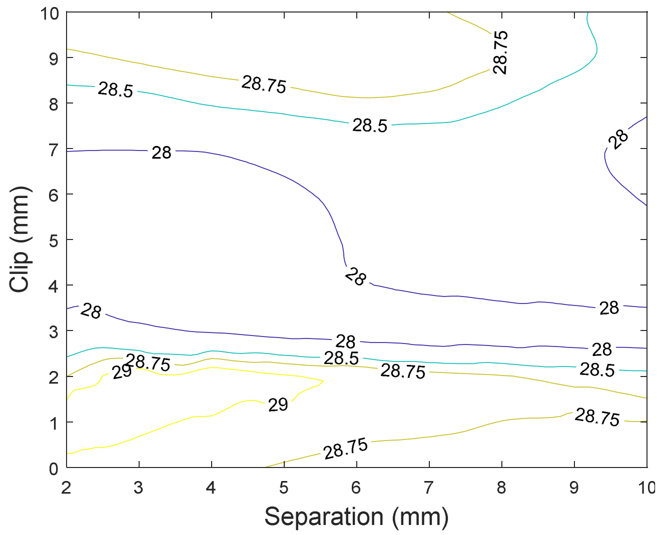

Figure 12: Peak Directivity for faceting parametric study with ε_r=2.9, from FEKO™..

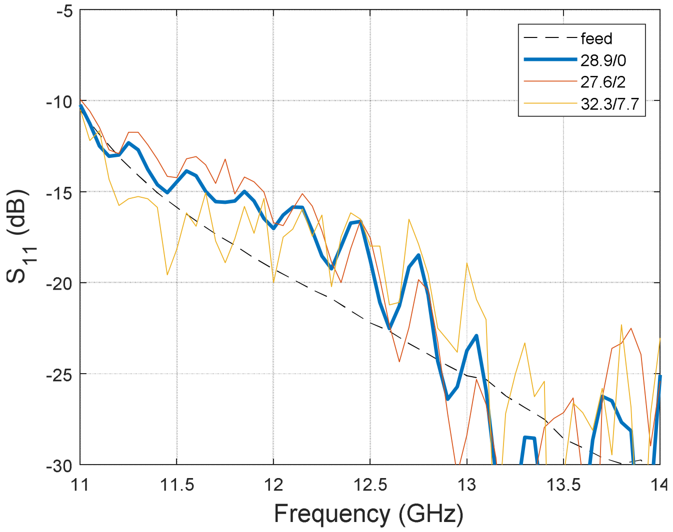

Figure 13: S_{11} frequency sweep of ε_r=2.1 lenses; labelled separation/clip, from FEKO™.

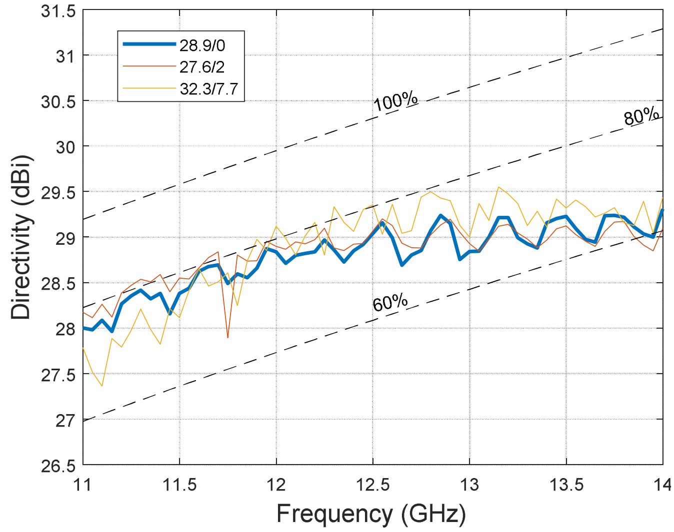

Figure 14: Directivity frequency sweep of ε_r=2.1 lenses; labelled separation/clip, from FEKO™.

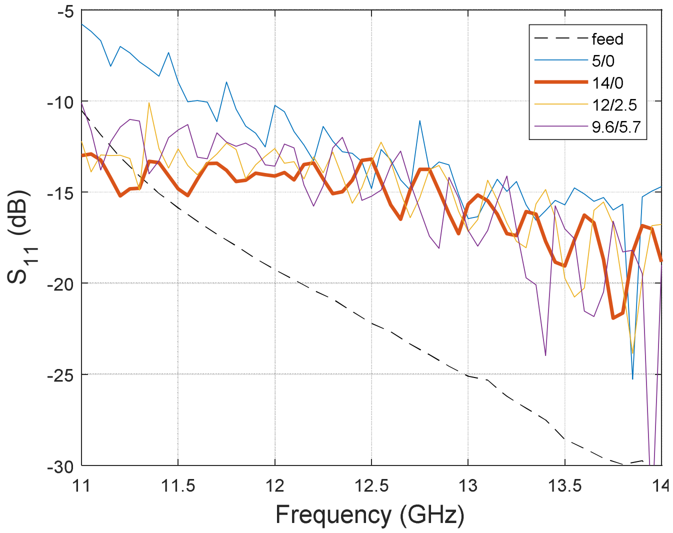

Figure 15: S_{11} frequency sweep of ε_r=2.54 lenses; labelled separation/clip, from FEKO™.

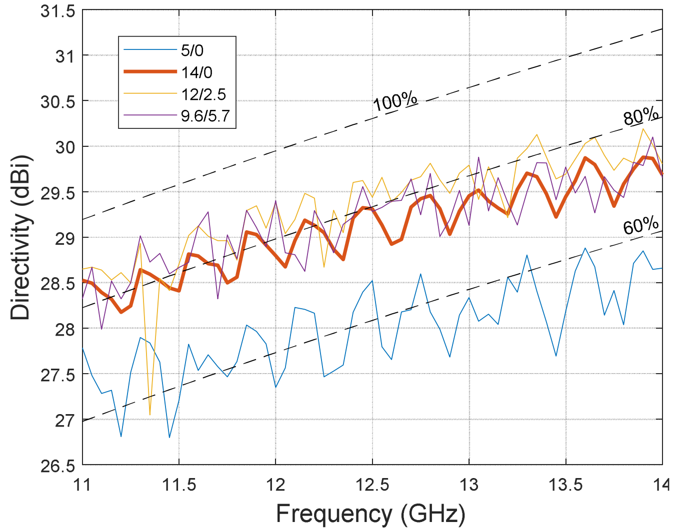

Figure 16: Directivity frequency sweep of ε_r=2.54 lenses; labelled separation/clip, from FEKO™.

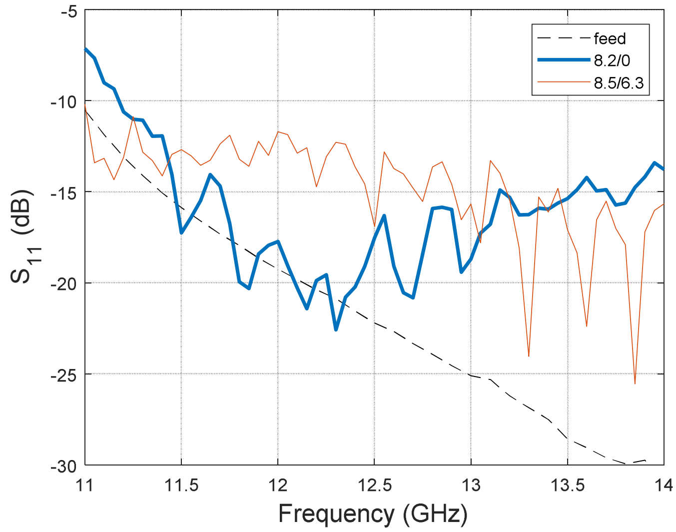

Figure 17: S_{11} frequency sweep of ε_r=2.7 lenses; labelled separation/clip, from FEKO™.

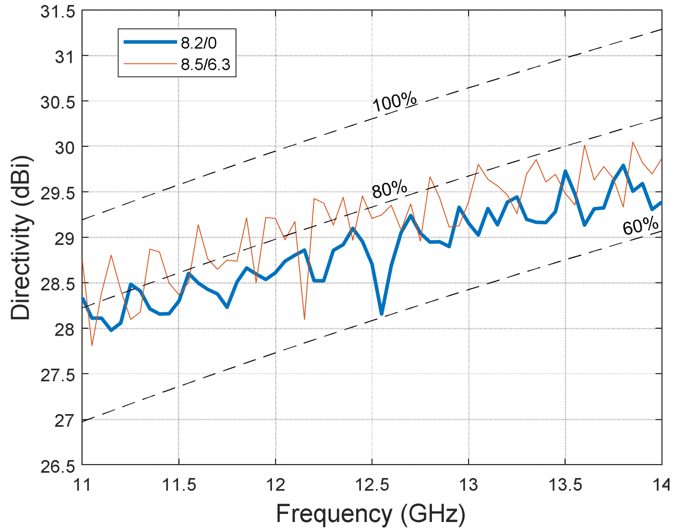

Figure 18: Directivity frequency sweep of ε_r=2.7 lenses; labelled separation/clip, from FEKO™.

The ε_r=2.7 spherical lens and faceted lens had radically different S_{11} characteristics, Figure 17. The general form of 8.5/6.3 is close to that of the ε_r=2.54 lenses, which is not surprising as the flat facet surface was 14.8mm from the scalar feed. This with the similarities between the ε_r=2.54 sphere at 5mm and the ε_r=2.7 at 8.2mm suggest that these lenses were too close to the scalar feed, and that these near positions should be avoided. The Directivity performance of the ε_r=2.7 8.5/6.3 was comparable to the ε_r=2.54 lenses giving 85% aperture efficiency across some narrow bands, Figure 18.

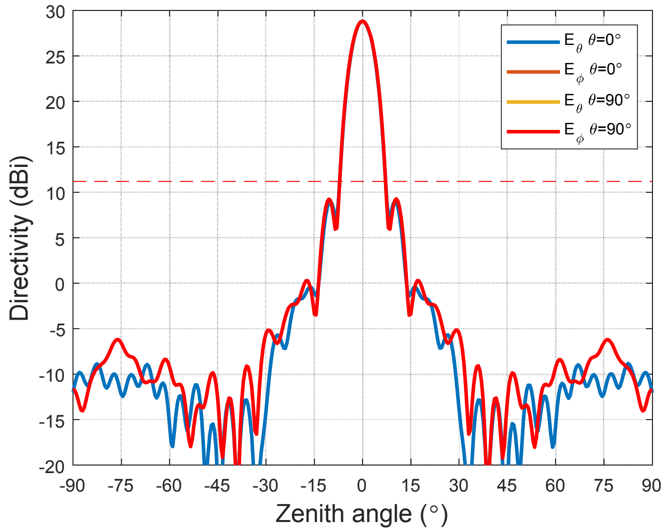

Figure 19: Radiation patterns of ε_r=2.54 sphere at 13.9mm separation from the feed at 12GHz; from FEKO™.

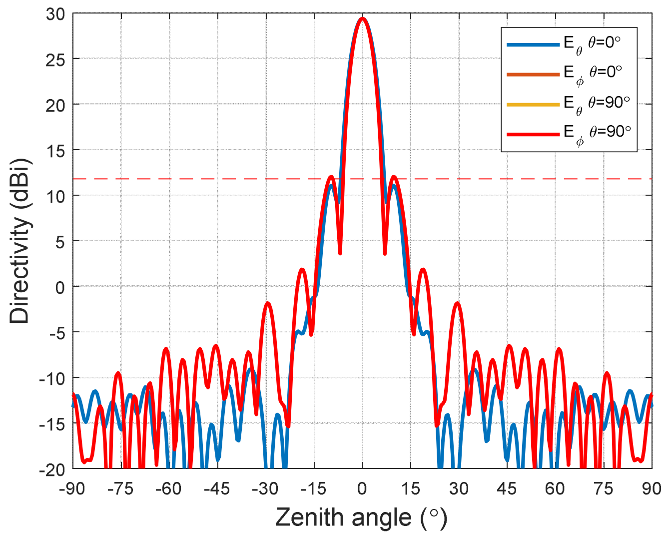

Figure 20: Radiation patterns of ε_r=2.54 lens with 2.5mm clip at 12mm separation above the feed at 12GHz; from FEKO™.

The radiation pattern of the ε_r=2.54 spherical lens was under-illuminated as evidenced by the first sidelobe level been below -17.6dB. In contrast, the "12/2.5" lens had sidelobes about -17.6dB showing the effects of facet in modifying the lens illumination.

5. Conclusions and future work

In a follow-up numerical study, the effects of faceting $5\lambda_0$ spherical lenses close to the illumination point was investigated for ε_r=2.1 to ε_r=2.9. For a single frequency the Directivity could be increased to give aperture efficiencies in the 85% to 90% range. At set of representative designs were simulated across 24% bandwidth, being about half what is required for Q-band. All the lenses had multiple S_{11} resonances and Directivity oscillation. Two cases of Directivity oscillation troughing were identified at 12GHz which biased the faceting parametric study. The implication is that parametric studies should be undertaken at multiple frequencies for this type of antenna which suffers from unpredictable resonances and oscillations.

Future work will consider multiple feeds to give multiple beam operation across a hemisphere, and work will be done on the lens support structure which is expected to further complicate lens behavior.

8. References

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