A Low Profile Radiating Element with Nearly Hemispheric Coverage for Satellite Communications On-The-Move Hybrid Array Antenna

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***Abstract*—A novel design solution of a dual-linearly-polarised Ku-band low-profile radiating element for low elevation angle coverage (down to 10° above horizon) is presented. Such an element is suitable for full-duplex Satellite Communications On-The-Move (SCOTM) hybrid scanned phased array antenna applications. Standard-designed radiating elements for array applications with low profile physical structure suffer poor low elevation angle coverage as the element pattern reduces by sine of the elevation angle. The element design demonstrated in this paper features unique louvered array element geometry incorporating a spatial "ray bending" lens facilitates the shaping of the element pattern to increase gain at low elevation angles. Preliminary modelling results using ray-tracing analysis shows that the desired low angle coverage can be achieved. Currently in progress full 3D electromagnetic simulations which include the interaction between the basic radiator and the spatial lens indicates that using an ideal tilted element with novel louvered reflector in addition with proposed lens, low angular coverage can potentially be realised in a low profile structure.**

***Index Terms*— Satellite Terrestrial Antennas, Vehicular Satellite Antennas, Satellite Communications On-The-Move, Phased Array Antennas**

I. INTRODUCTION

In recent years, Satellite Communications On-The-Move (SCOTM) is gaining great interests in commercial, emergency services and military utilities. SCOTM antennas play the key role in SCOTM operations. A low profile SCOTM antenna with planar physical structures is very desirable because it minimises the aerodynamic drag and visual impact. Therefore, array technology is sought. Currently there are many reception-only (down-link) SCOTM services, but duplex SCOTM service that provides both satellite up-link and down-link communications is preference.

A basic SCOTM operational scenario is shown in Figure 1. The antenna beam must remain "locked" in the direction of the desired satellite during movement, and the polarisation must remain aligned with the satellite. During the most severe tilt conditions of the vehicle (e.g. the car is climbing up a hill), the satellite appears to have a much lower elevation angle to the low profile antenna mounted on the car roof. The antenna beam will have to be steered downwards to point at the satellite in order to maintain the link. For an ideal flat aperture antenna, the gain is proportional to the projected area of the antenna aperture in the direction of the satellite which reduces by sine of the elevation angle. SCOTM array antennas employing standard radiating elements typically suffer from low elevation angle coverage deficiency.

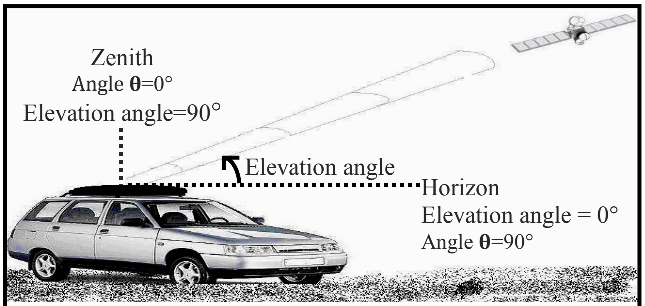

Figure 1. Basic SCOTM operational scenario

II. DESIGN CHALLENGES & EXISTING SCOTM ANTENNAS

The design challenge is to improve the element gain at low elevation angles while maintaining a low profile physical structure. A number of existing design approaches for SCOTM antennas in Ku-band have been researched and some of them are also commercially available [1-5]. They are divided into non-planar and planar categories. Non-planar antennas such as reflector solutions typically require large volume and hence do not meet the low profile requirement. Planar (or nearly planar) phased array antennas are therefore more suitable to potentially meet the low profile requirement. Planar phased array antennas fall into two types: 2D electronically scanned and hybrid scanned. The hybrid scanned antennas mechanically scan the antenna beam by rotation in azimuth angles and electronically scan in the elevation plane. Clearly, the hybrid scanned solution facilitates a simpler and lower cost feed network design. Most existing hybrid scanned phased array antenna designs demonstrate poor low elevation angle coverage performance and are mainly designed for receive (down-link) only.

III. PROPOSED DESIGN SOLUTIONS

To overcome the lack of gain for low elevation angles of a standard-designed element, energy in such an element radiation pattern needs to be "re-focused" to the low elevation angle coverage region. Because such a "re-focused" element is used for hybrid array applications that the azimuth scanning is by mechanical rotation and elevation scanning is electronic, the "re-focused" element radiation pattern does not need to be symmetric and therefore can be designed to be tilted to enhance low elevation angle gain performance. The proposed low profile element which incorporates a multi-layered dielectric lens for near hemispheric coverage in a hybrid scanned phased array antenna that potentially provides good low elevation angle coverage down to 10°. The proposed element utilises a louvered reflector which allows the basic radiator to be tilted $\alpha°$ (= 15°) from horizon to lower elevation angles with minimum blockage and the multi-layered dielectric lens bends the element radiation pattern further down to lower elevation angles. A cross-sectional view of the proposed low profile elements in a planar hybrid phased array antenna is shown in Figure 2. The proposed design structure is placed on a mounting plate and covered with a radome.

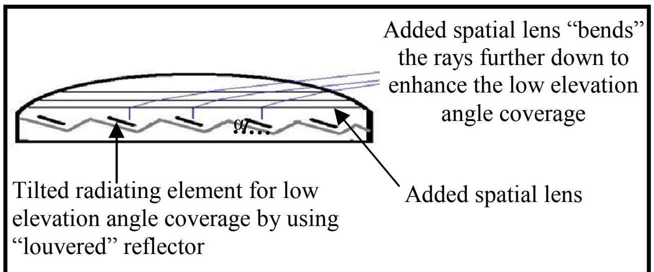

Figure 2. Proposed design structure

IV. PRELIMINARY DESIGN STUDIES

Preliminary design and modelling has been carried out based on ray-tracing with assumptions of isolated and ideal radiating elements. Under these conditions the effects of interactions with the lens and the mutual coupling between elements are not taken into account.

A. Ray Tracing analays of the Proposed Design Structure

It is well known that the radiation from a single element source can be considered as a spectrum of plane waves [6]. The spectrum of plane waves produced by a single non-tilted element source passing through the lens will be symmetrically bent to low elevation angles as shown in Figure 3-a. For the case of a tilted single radiating element source, an asymmetric pattern is produced with maximum beam steering towards lower elevation angles on one side as desired (Figure 3-b). As discussed previously, the array antenna is mechanically rotated in azimuth and therefore does not require a symmetrical element radiation pattern. This means that higher element gain can be realised over the required elevation scan range than would be possible with a symmetric design. The proposed lens analysed here is considered to have infinite transverse dimensions in the horizon plane.

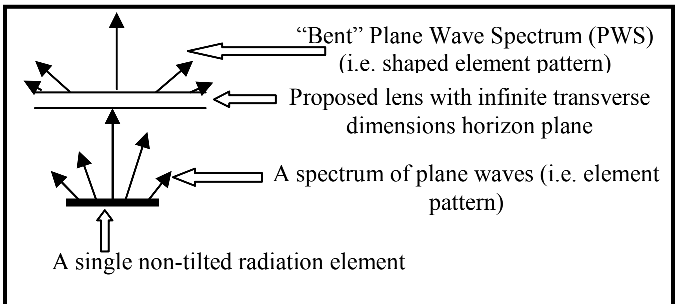

Figure 3-a. Non-titled element with proposed lens

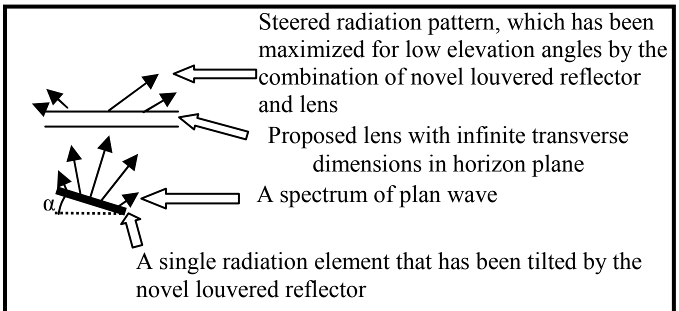

Figure 3-b. Titled element with proposed lens

B. Mathematical Modeling of the Proposed Dielectric Lens

The cross-sectional view of the proposed multi-layered dielectric lens is presented in Figure 4. The proposed dielectric lens consists of three layers that have dielectric constant values equal to εa, $\varepsilon 1$ and $\varepsilon 2$. A wedge-shaped dielectric is used as the first layer and its thickness is dependent on the tilt elevation angle α of the radiating element as the radiating element is immersed in the first layer. The tilt angle α is chosen to be 15° to steer the radiating element pattern towards lower elevation angles without blocking radiation from adjacent elements on the array face. Ono top of the first layer two dielectric slabs are used as the second and third layers. The thicknesses of the second and third layers of the proposed lens are selected as L1 and L2 respectively. A multi-layered dielectric structure with descending epsilon values is proposed for maximum ray bending towards lower elevation angles with minimum internal reflections.

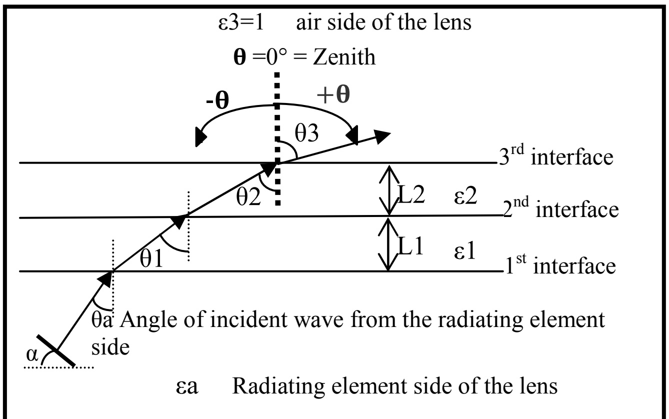

Figure 4. Cross-sectional view of the proposed lens

The transmission and reflection properties of the proposed lens are mathematically modelled using MathCAD software. The angle of the incident wave is set as a variable, $\boldsymbol{\theta a}$, that has a range between –90° and 90° and using well known Snell's Law of refraction, refracted angles $\theta 1$, $\theta 2$, and $\theta 3$ at each interface can be calculated as follows,

$$\theta 1 = \sin^{-1}\left[\sqrt{\frac{\epsilon a}{\epsilon 1}} \times \sin\left(\theta a \times \frac{\pi}{180}\right)\right]$$

$$\theta 2 = \sin^{-1}\left[\sqrt{\frac{\epsilon 1}{\epsilon 2}} \times \sin \theta 1\right]$$

$$\theta 3 = \sin^{-1}\left[\sqrt{\frac{\epsilon 2}{\epsilon 3}} \times \sin \theta 2\right] \quad (1)$$

Field transmission parameters [7] for both perpendicular and parallel polarisations are utilised in the MathCAD modelling. Power transmitted for both perpendicular and parallel polarisation are obtained as follows,

- For parallel polarisation:

Power Transmitted $=1-(|\Gamma 1\_PAR|)^2$,

- For perpendicular polarisation

Power Transmitted $= 1-(|\Gamma 1\_PER|)^2$

Where $(|\Gamma 1\_PER|)^2$ and $-(|\Gamma 1_PAR|)^2$are reflection coefficients at the 1st interface.

Parametric studies to maximise the ray banding property of the proposed lens have indicated optimum values of εa=6, ε1= 3, L1 = 2mm, ε2= 2 and L2 = 2.6mm.

C. Mathematical Modeling of the Radiating Element Source Pattern in Air and the Resultant Patterns

The radiating element source is designed to be dual-linearly polarised. Therefore, an element source is fed by two excitations with orthogonal polarisations (polarisation 1 and 2) simultaneously. Particular attention is paid to the electronically scanned plane (scan plane) which is the E-plane pattern for parallel polarisation (1) and H-plane pattern for perpendicular polarisation (2) referenced to the plane of incidence.

For an ideal single radiating element tilted at an angle of 15° to the horizontal in free space (Figure 5-a, Figure 5-b), the far field radiation pattern approximations were obtained on MathCAD .The E-plane pattern for parallel polarisation and the H- plane pattern for perpendicular polarisation of a single titled element source are shown in Figure 5. The element is titled α degree in elevation by the novel louvered reflected in the scan plane. The optimum value of α is selected to be 15° as stated before.

As anticipated, asymmetrical patterns are obtained for a tilted element source in comparison with the same radiating element source that is not tilted (Figure 6-a, Figure 6-b). Such asymmetric patterns are leaned towards the **θ** positive direction with maximum gain of shifted from at zenith to an elevation angle of 15° down from zenith.

When such a tilted radiating element is immersed in the first layer of the proposed multi-layered dielectric lens, far field patterns of the overall structure can be obtained by applying the transmission coefficients calculated previously of the proposed lens to the radiating element source patterns. In addition, a correction gain ratio **Δ**g is added for more accurate results prediction. The final resultant E-plane pattern for parallel polarisation and H-plane pattern for perpendicular polarisation are presented in Figure 7.

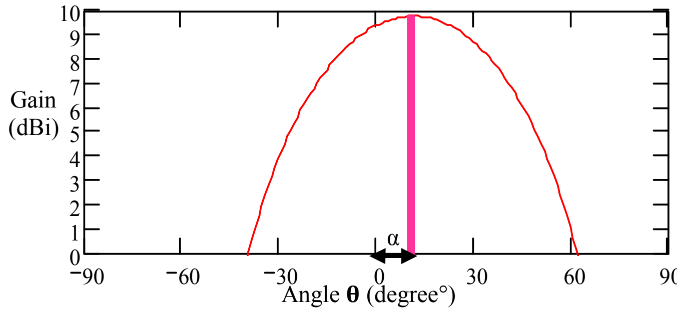

Figure 5-a. E-plane pattern of a tilted single element source in air for parallel polarsation

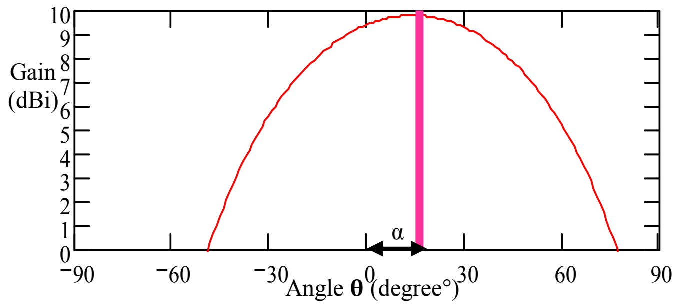

Figure 5-b. H-plane pattern of a tilted single element source in air for perpendicular polarisation

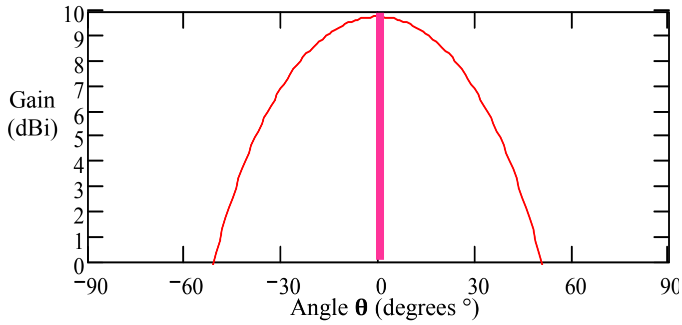

Figure 6-a. E-plane pattern of a non-titled element source in air for parallel polarisation

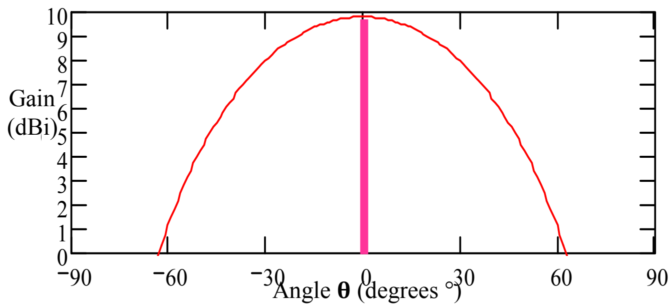

Figure 6-b. H-plane pattern of a non-titled element source in air for perpendicular polarisation

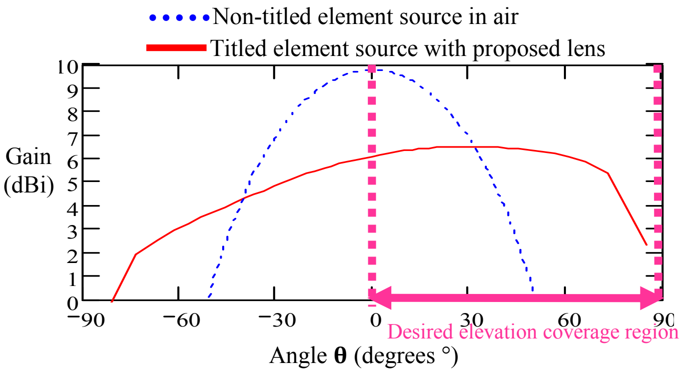

Figure 7-a. E-plane patterns for parallel polarisation

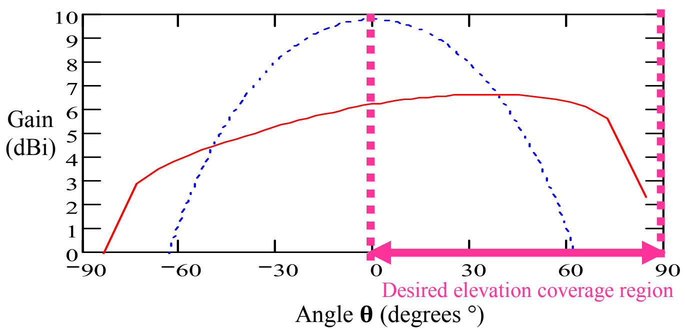

Figure 7-b. H-plane patterns for perpendicular polarisation

It is apparent that when the proposed multi-layered dielectric lens is applied in combination with the novel louvered reflector, the resultant scan plane far filed patterns (E-plane for parallel polarisation and H-plane for perpendicular polarisation) are widened indicating gain enhancement at lower elevation angles. The asymmetric natures of the patterns are evident in each case; the gain around zenith is reduced compared with a non-titled element source patterns, the energy is "re-focused" on one side as desired. The resultant parallel polarisation E-plane pattern peaks at 28° downwards from the zenith with a maximum gain of 6.5dBi. The maximum gain 6.6dBi for perpendicular H-plane resultant pattern occurs at **θ**=36° in elevation measured from zenith.

For the case of E-plane far field pattern of parallel polarisation, the dramatic low elevation angle gain enhancement takes place at from 60° to 73° measured downwards from zenith with gains improved by 6.5dB to 5.5dB. At very low elevation angles (**θ** is between 73° and 85°) that are close to the horizon, an average gain enhancement of 3.9dB is achieved.

Resultant H-plane pattern for perpendicular polarisation has also shown great low elevation angle gain improvement with more gain transformed away from zenith to the desired side of the horizon direction. For **θ** angles between 56° and 73° from zenith, the gains are improved by 6.4dB to 5.6dB. For very low elevation angles (**θ** is between 73° and 85°), gains are improved by 3.9dB on average.

V. Preliminary 3D Electromagnetic Simulation Results

A full 3D EM simulation for the multi-layered antenna structure shown in Figure 4 has been undertaken using CST Microwave Studio software. A square Ku-band waveguide section was used as the basic radiating element and the dimension of the lens is selected to be 15mm. The geometry in this case has been altered to allow excitation of the waveguide by tilting the proposed dielectric multi-layered lens by an angle of 15º.

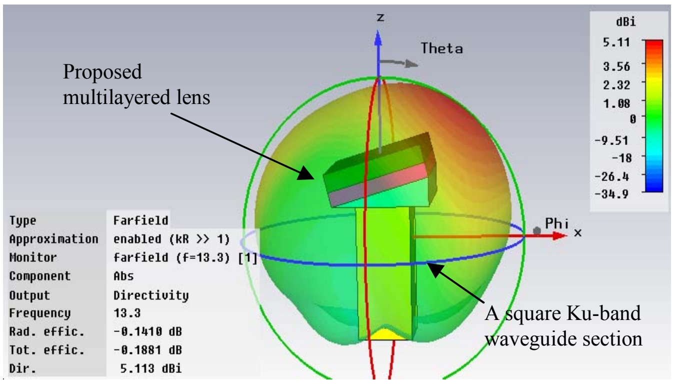

Figure 8. An outline of the far field pattern for the waveguide element and lens rearrangement at 13.3GHz

An outline of the far field radiation pattern relative to the antenna geometry with proposed lens is shown in Figure 8 at the middle frequency 13.3 GHz of the transmission and reception bands.

Examinations of the 2D polar plots of the resultant far filed patterns at 13.3GHz for both parallel and perpendicular polarisations are shown in Figure 9.

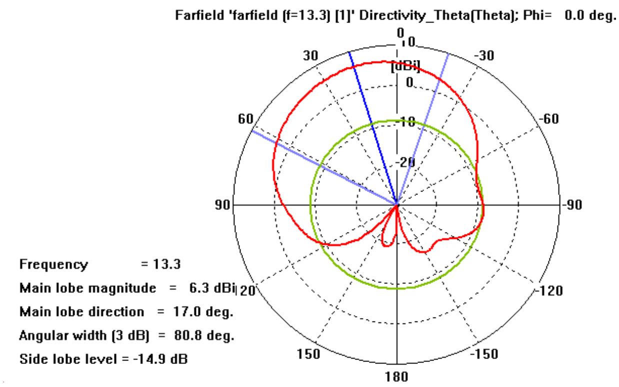

Figure 9-a. Resultant E- plane pattern for parallel polarisation

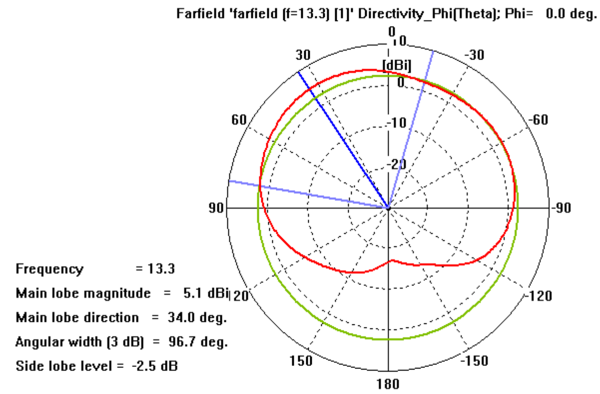

Figure 9-b. Resultant H-plane pattern for perpendicular polarisation

It is observed that, for the parallel polarization, when the radiating element source is immersed in the first layer of the proposed multi-layered lens, the resultant patterns energy are "dragged" to the desired low elevation angle region as predicted in mathematical modeling. The resultant E-plane pattern (Figure 9-a) is steered away from zenith towards lower elevation angles with maximum beam direction at 17° measured from zenith. The resultant H-plane pattern for perpendicular polarization (Figure 9-b) has tilted the main beam lobe towards lower elevation angle with the main beam lobe direction at 34° measured from zenith.

As expected, the simulation results presented above which the proximity effects of the lens to the radiating element and the finiteness of the lens geometry were taken into account for, showed slight variation compared with the mathematical modeling results. It is believed that, the finiteness of the lens geometry that inducing edge effects is dominating the slight pattern fluctuation. Simulations with larger-dimensioned lens and sub-array structures have been carried out for further investigations on the proposed design.

VI. Conclusion

This paper has presented a novel design solution of a low profile radiating element for Ku-band duplex Satellite Communication On-The-Move (SCOTM) hybrid scanned phased array antenna applications. Such a design solution incorporates the use of a louvered array element reflector in combination with a multi-layered dielectric lens for gain enhancement at low elevation angles. The novel louvered reflector of the element tilts the element pattern towards low elevation angles while the proposed dielectric lens "bends" the tilted rays further maximising low elevation angle coverage performance. The preliminary design modelling presented has demonstrated very promising results. This has proved that using an ideal tilted element with a novel louvered reflector in addition to the proposed lens, low angular coverage can be realised in a low profile structure.

Current 3D simulation results of the preliminary design indicate potentially very positive performance of the proposed lens and novel louvered element reflector geometry. However, further investigations and analyses need to be carried out to reinforce the preliminary conclusion. Further research work includes simulation of the proposed design solution in a sub-array environment to include mutual coupling effects and the fabrication of a sub-array based on the proposed design. The design feasibility of the proposed multi-layered lens and the louvered reflector will be experimentally confirmed in the very near future.

Acknowledgment

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