Circularly polarized multi-beam lens antenna system for High Altitude Platforms (HAPS)

Marco Letizia, Jean-François Zürcher, Benjamin Fuchs, Juan Ramon Mosig, Anja Skrivervik

Laboratory of Electromagnetics and Acoustics (LEMA), Ecole Polytechnique Fédérale de Lausanne (EPFL), Switzerland
marco.letizia@epfl.ch

Abstract:—**In this paper a 30 GHz multi-beam antenna prototype has been developed for High Altitude Platform Stations (HAPS) applications. When mounted on a HAPS at the stationary altitude of 21Km, this antenna provides cellular coverage on the ground. The antenna consists of a dielectric lens fed by circular waveguides terminated with small horns. Circular polarization is achieved by integrating a polarizer in the waveguide feed. Due to the lens symmetry, each beam presents the same radiation pattern. The global antenna system has been designed, realized and measured. The prototype fulfils the initial specifications and shows an impedance bandwidth at -10 dB of 19%. Moreover an axial ratio lower than 3 dB is achieved within this bandwidth in a ± 5° angular range.**

Keywords: ***lens antenna; multi-beam antenna; circular polarization; septum polarizer; waveguide feed; horn; HAPS.***

I. INTRODUCTION

Communications via High Altitude Platforms System (HAPS) are expected to provide broadband capability from aerial platforms, thus delivering cost effective solutions. It provides a viable alternative to cable and satellite with the potential to reach rural, urban and travelling users.

HAPS are airships or planes, operating in the stratosphere, at altitudes of typically 17 – 22Km (around 75,000 ft). At this altitude (which is well above commercial aircraft height), they can maintain a quasi-stationary position, and support payloads to deliver a range of services: principally Communications, and Remote Sensing.

This work has been performed in the frame of a project financed by the Swiss federal fund of technology transfer CTI [1]. Its objective is to develop a multi-beam antenna system suitable for HAPS.

II. SCENARIO

The selected scenario corresponds to a concept currently under investigation in Switzerland. It consists of a Ka-band (27.5-31.3 GHz) multi-beam antenna mounted on a balloon platform at the standard height of H_{HAPS} = 21 Km and providing 7 spot beams on the ground [2]. This antenna should allow for multi-cell architecture and for spectrum re-use [3-6].

From global system considerations (Table I), it was determined that the spot beams should be arranged in a overlapping hexagonal grid, and every beam should guarantee an effective ground coverage in the form of a 5 Km diameter circular cell (Figure 1, with 2**Rcell* = 5 Km). Since in this scenario the beams are arranged in a hexagonal grid, the beams overlap level is chosen at -4 dB. The circular cell boundary on ground therefore corresponds to a -4 dB beam aperture. The Field of View (FoV) angle associated to this cell diameter is simply given by (see Figure 1)

$$\mathrm{FoV} = 2\arctan(R_{cell} / H_{HAPS}) = 13.6° \tag{1}$$

This value could also be considered to be an external specification for our antenna. Finally, it must be mentioned that in this particular project, global budget link considerations called for a minimum antenna gain of G = 19 dB.

III. ANTENNA DESIGN

The antenna is composed of seven identical elementary radiators that feed a dielectric lens. Every elementary radiator consists of a circular waveguide terminated with a short horn. These elementary radiators can handle a relatively high power, while providing an excellent circular polarization and a reasonable angular range in a wide bandwidth [7].

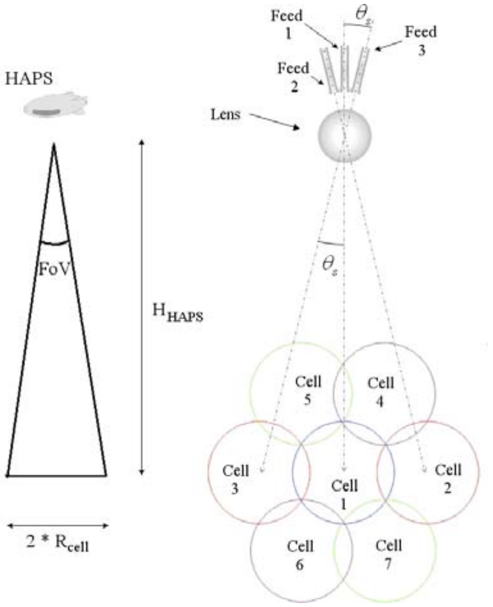

Figure 1. HAPS downlink geometry applied to 7 cells arranged in a hexagonal grid with a simplified antenna system.

Frequency	27.5-31.3 GHz
Bandwidth	3.8 GHz (≈13%)
R_{cell}	2.5 Km
H_{HAPS}	21 Km
FoV	13.6°
G	19 dB

Table I. HAPS link scenario

In order to produce seven cells on the ground (as shown in Fig. 1), seven independent beams have to be radiated by the lens. By placing seven feeds at the same distance from the surface of the lens, seven identical beams are generated (provided that the mutual coupling is low). Each feed radiates broadside and properly illuminates the lens. The lens focuses the radiation coming from every feed and shapes it into a directive beam. Each feed has to be positioned around the lens (see Fig. 1) in such a way that each beam points to the corresponding cell centre on the ground and all the feeds' longitudinal axes intersect at the centre of the lens. From geometrical considerations, the distance between adjacent cell centers is given by:

$$d_{ac} = 2\, R_{cell} \cos 30° = 4.33 \text{ Km}. \qquad (2)$$

In turn, this distance determines the angular position of the feeds around the lens, guaranteeing adequate coverage of the ground. The angle between adjacent feeds must be:

$$\theta_S = \arctan(4.33 /\ H_{HAPS}) \ = \ 12° \qquad (3)$$

slight smaller than the *FoV*, due to the pattern overlapping.

Figure 3 is a schematic view of a circular waveguide feed that illuminates the lens. Figure 2 and Table 2 report the septum polarizer dimension. The coaxial to waveguide transition allows exciting the fundamental mode in circular waveguide. This transition determines the bandwidth of not only the waveguide feeding but also the whole lens antenna. Since the fundamental mode in circular waveguides is linearly polarized, a polarizer is necessary to achieve circular polarization (Fig. 2). Finally, since the waveguide open end constitutes a strong discontinuity for the propagating waves, a horn is needed to provide a smooth transition to free space, matching the impedance while avoiding internal reflections. Moreover, the horn helps to illuminate the lens properly. All the feed parts were optimized to improve both the axial ratio and the reflection coefficient of the structure.

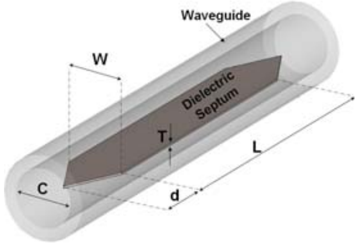

Figure 2. Polarizer model with the notations used for the design.

L	6.20 mm
d	10.67 mm
C	7.30 mm
T	1.02 mm
W	7.20 mm

Table II. Polarizer dimensions

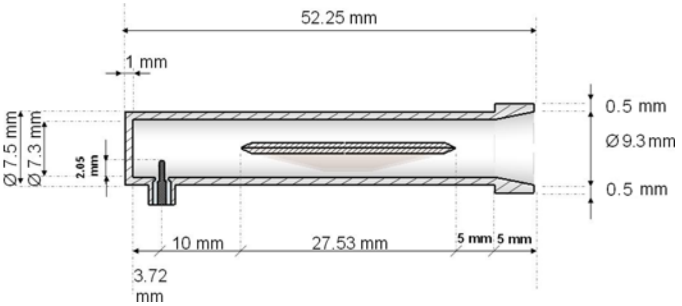

Figure 3. Feed model cut view and dimensions.

The lens radius *R* and the distance *F* between the lens center and the feed aperture are obviously the most critical parameters influencing the beam pattern. They are optimized to find the best trade-off between maximum directivity, *FoV* and best reflection coefficient. *F* can be roughly approximated by the homogeneous dielectric lens focal point distance, given by [8]:

$$F \approx \frac{nR}{2(n-1)} \qquad (4)$$

where n is the refractive index of the lens material ($n \approx 1.44$ for Teflon). This value can be used as starting point to speed up the numerical optimization (performed by CST Microwave Studio®), which finally yields F = 49 mm and R = 30 mm as optimized values (See Fig. 4).

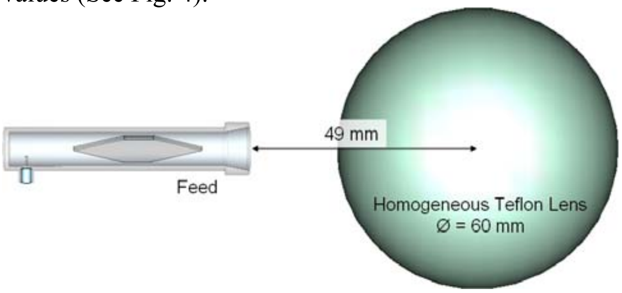

Figure 4. Single beam antenna model with relevant dimensions.

In the next step, the full multi-beam antenna system has been modelled by positioning 7 feeds around the lens, as shown in Fig. 5. The angle between two adjacent beams is θ_s = 12°, as explained in Section II. The distance between the lens centre and each horn aperture is kept at 49 mm. The polarizers are positioned within each feed in order to radiate RHCP field.

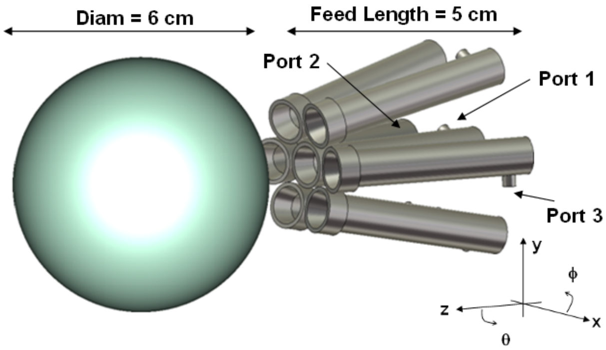

Figure 5. Multi-beam antenna model.

IV. FEED PROTOTYPE AND MEASUREMENTS

Primary sources, dielectric polarizers and Teflon lens have been realized by milling machine techniques with a nominal tolerance of 50 µm. A metal adjuster tool (Fig. 6a) has been machined to accurately align the dielectric septum inside the waveguide (Fig 6b) before mounting the connector. Thanks to this tool, few operations are needed to change the antenna polarization. Fig. 7 is a picture of a single feed prototype with a mounted coaxial connector; the dielectric slab polarizer is inside the waveguide, and the horn shape is integrated into the waveguide inner profile.

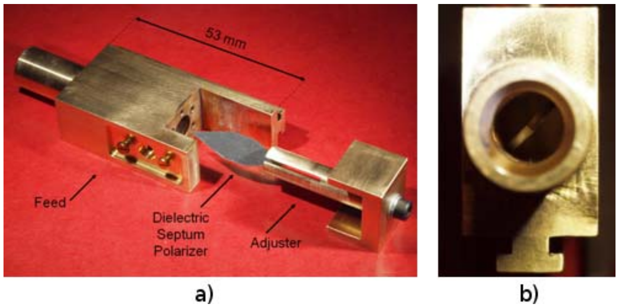

Figure 6. Single feed realization: a) the dielectric polarizer is introduced in the waveguide structure by using a proper adjuster; b) the polarizer is fixed inside the waveguide.

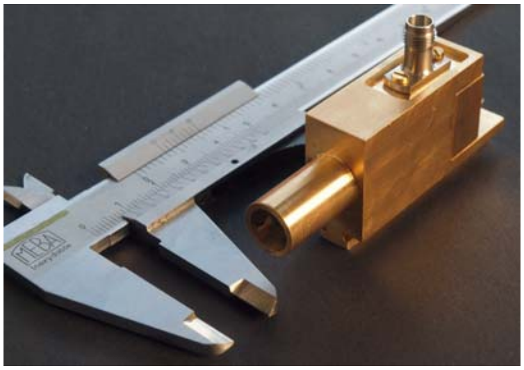

Figure 7. Single feed prototype with a mounted coaxial connector: the dielectric slab polarizer is inside the waveguide, and the horn shape is integrated in the waveguide inner profile.

The scattering parameters of this structure have been evaluated by the vector network analyzer (Agilent Technologies E8361A). Fig. 8 shows the reflection coefficient of the primary feed (with and without polarizer) and the excellent bandwidth achieved. Measurements in the anechoic chamber show the quality of the circular polarization of the primary source. The axial ratio (see Fig. 9) is better than 2 dB within the working frequency band and for -30°<θ<30°. The HPBW of the feed is about 60°, its radiation pattern is symmetric and stable within the frequency band of interest.

Measurements confirm that the polarization of the antenna system shown in Fig. 9 can be easily changed from RHCP to LHCP by rotating the polarizer septum 90° along its major axis. RHCP and LHCP antenna performances are quite similar, as expected.

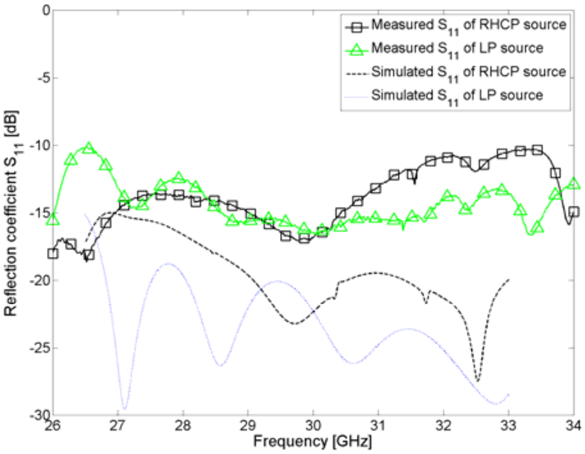

Figure 8. The performances of the primary source alone. RHCP is achieved by introducing the dielectric septum polarizer inside the feed and LP (linearly polarized) is achieved without polarizer.

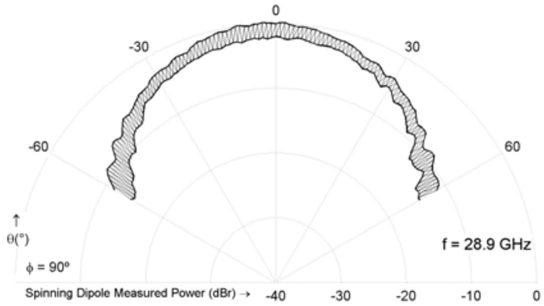

Figure 9. The spinning dipole measurement of the primary source alone. The axial ratio is below 2 dB for θ between ±30° and within the freqencies band of interest.

V. LENS ANTENNA PROTOTYPE AND MEASUREMENTS

A holed plastic frame (Fig. 10) has been machined in order to keep the lens and the feeds in place for anechoic chamber measurements. The feeds are placed in the focal region of the lens at a distance *F* of 49 mm.

A. S-ParametersParameters

Figure 11 provides the measured S-parameters for the multifeed antenna in presence of the lens (complete system). Port 1, 2, 3 are defined as in Fig. 1 and 5. For symmetrical reasons, only S_{11}, S_{21} and S_{23} have been measured. For the most sensitive parameter, S_{11}, Fig. 11 also includes S_{11} simulated results. A good agreement between theory and measurements can be observed. Moreover, a comparison with Fig. 8, show that the measured reflection coefficients of the feed alone and with the lens are similar. This proves that the bandwidth of the antenna system is mainly determined by the bandwidth of the primary source.

The coupling between adjacent feeds (see S_{21} and S_{23} in Fig. 11) is lower than -32 dB over the whole frequencies band, which is rather low. Since the coupling between feeds is very low, the performance of one waveguide feed is not influenced by the presence of the others and the multi-beam antenna system could be easily designed focusing attention on only one feed. Moreover, although there is more space between feed 2 and 3 than between feed 1 and 2 (see Fig. 1), S_{23} is in average a bit higher than S_{21}. This may be explained by the orientation of feeds 2 and 3. The energy radiated by the feed 2 is captured more easily by feed 3 than feed 1. This could explains the difference between S_{21} and S_{23}.

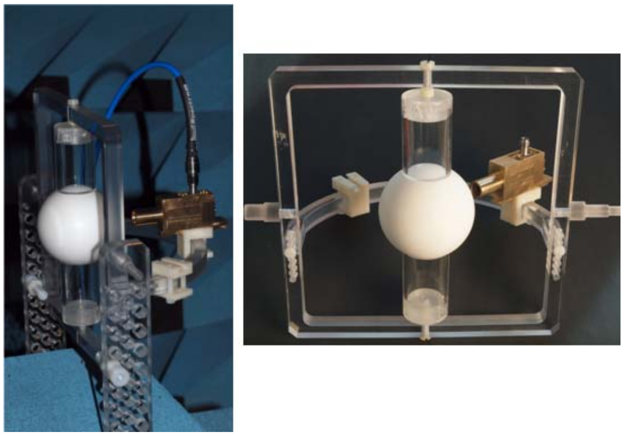

Figure 10. Prototype of the dielectric lens fed by a waveguide terminated by a short horn: the septum polarizer is embeded in the feed.

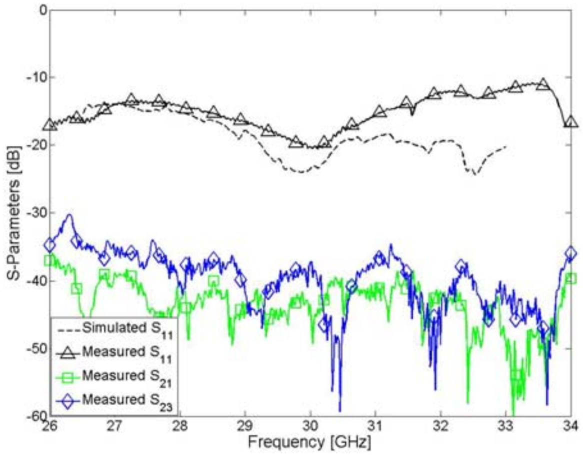

Figure 11. Performances of the lens antenna: return loss, coupling between feed 1 and feed 2 and coupling between feed 2 and 3.

Since in the proposed antenna system, each radiated beam can have both right-hand circular polarization (RHCP) and left-hand circular polarization (LHCP) depending on the position of the polarizer, the coupling between feed 1, and feed 2 (see Fig. 5) has been compared for the two following cases:

- feed 1 and 2 both radiate a RHCP field;
- feed 1 radiates RHCP and feed 2 radiates LHCP.

Figure 12 shows that the coupling between adjacent feeds increases when the 2 primary sources radiate with opposite polarizations. This phenomenon is probably due to partial reflections in the lens' surface, reversing the wave polarization. These considerations have to be taken into account when the clusters performances are evaluated (especially for communication system based on polarization diversity).

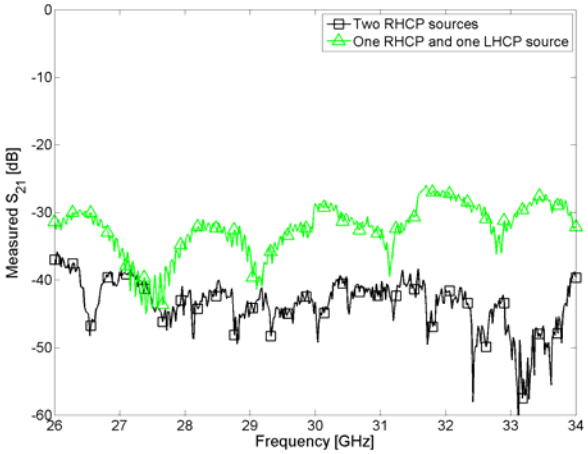

Figure 12. Coupling between two adjacent feeds (feed 1 and feed 2): in case of two RHCP sources the coupling is lower than the case of one RHCP and one LHCP source.

B. *Farfield radiation pattern measurements*

The farfield pattern of the lens antenna (only the central feed is active) is plotted in Fig. 13. The agreement between measurements and simulation is good. The half- power-beamwidth (HPBW) of the lens antenna is 11.8°, the beamwidth at -4 dB is 13.2° and the side lobe level (SLL) is lower than -15°, as expected from simulations.

The axial ratio has been measured with the spinning dipole method for different frequencies (between 27 and 32.5 GHz) and angular values (θ=0°, θ±5°, θ±15°). The average values are plotted in Fig. 14. The axial ratio is acceptable (lower than 3 dB) over the whole frequencies band of interest (27.5 – 31-3 GHz) and within the interval angle of $-5° < \theta < 5°$.

Let us note that the presence of the lens slightly degrades the quality of the circular polarization (about 1 dB) in the broadside direction (θ=0°). This degradation become more important when one gets further to the broadside direction. This phenomenon can easily be explained through geometrical considerations. A solution to overcome this drawback is under investigation.

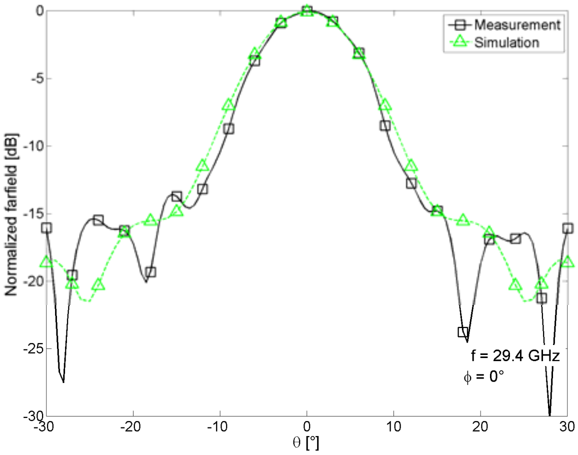

Figure 13. Farfield radiation pattern of the lens fed by one primary source at 29.4 GHz: comparison between simulation and measurements.

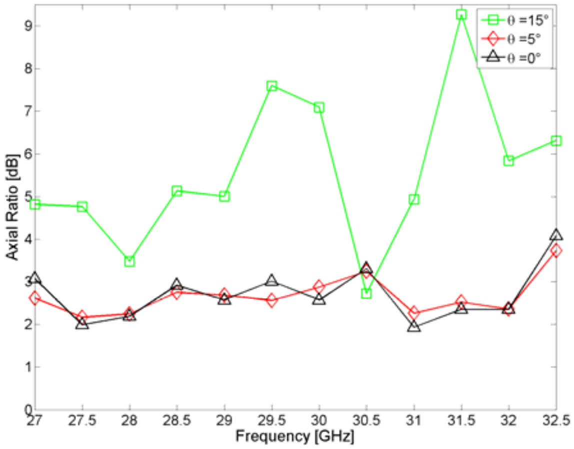

Figure 14. Measured axial ratio as a function of the frequency for 3 angular directions.

VI. CONCLUSION

A 30 GHz multi-beam antenna suitable for HAPS wireless applications has been presented in this paper.

A set of well-known elements (coaxial excitation, circular waveguide, septum polarizer, circular horn and homogeneous dielectric lens) has been carefully optimized together in order to produce a functional concept, demonstrated by a prototype. The antenna is based on seven identical elementary radiators that feed a dielectric lens. Every elementary radiator consists of a circular waveguide supporting internally a dielectric septum polarizer and terminated with a short horn. These elementary radiators can handle relatively high powers, while providing excellent circular polarization and a reasonable bandwidth meeting the system specifications. Moreover, anechoic chamber measurements show that the mutual coupling between adjacent elementary radiators (and hence between adjacent beams) can be easily mastered and kept at low levels. With a relatively easy fabrication process and an excellent mechanical robustness, these radiators are good candidate for the antenna feed system in a HAPS platform.

However, the presence of the lens slightly degrades the quality of the circular polarization of the feed, especially going away from the broadside direction. A solution to overcome this drawback is under investigation.

REFERENCES

[1] "F*easability study for HAPS antenna*", Swiss CTI project Nr 9301.1 PFNM-NM.

[2] T. C. Tozer and D. Grace, "High-altitude platforms for wireless communications," *IEE Electronics and Communications Engineering Journal,* **13**, June 2001, pp. 127-137.

[3] J. Thornton, "Properties of Spherical Lens Antennas for High Altitude Platform Communications," *6th European Workshop on Mobile/Personal Satcoms & 2nd Advanced Satellite Mobile Systems (EMPS & ASMS),* 21-22 Sept. 2004. ESTEC, European Space Agency.

[4] J. Thornton, D. Grace, C. Spillard, T. Konefal and T. C. Tozer, "Broadband communications from a high altitude platform - The European HeliNet programme," *IEE Electronic Communication Engeneer Journal,* **13**, June 2001, pp. 138-144.

[5] M. A. Mitchell, J. R. Sanford, L. E. Corey, R. A. Moore and V. P. Pusateri, "A multiple-beam multiple-frequency spherical lens antenna system providing hemispherical coverage," *ICAP 89,* 1989, pp. 394-398.

[6] J. Thornton, "Antenna Technologies for Communications Services from Stratospheric Platforms," *4th International Airship Convention and Exhibition, Cambridge*, UK, July 2002.

[7] M. Letizia, B. Fuchs, A. Skrivervik, J.M. Mosig, "Circularly Polarized Lens Antenna System Providing Multibeam Radiation Pattern for HAPS", Radio Science Bulletin, March 2010.

[8] B. Schoenlinner, W. Xidong, J. P. Ebling, G. V. Eleftheriades, G. M. Rebeiz, "Wide-Scan Spherical-Lens Antennas for Automotive Radars," *IEEE Transactions on Microwave Theory and Techniques,* **50**, 9, 2002, pp. 2166-2175.