Mm-Wave Beam Steering Antenna Based on Extended Hemispherical Lens Antenna Subarrays

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***Abstract*— A mm-wave beam steering antenna based on L lens antenna subarrays (LASs) is presented. Different from the recent work, the antenna employs extended hemispherical dielectric lenses and achieves 2D beam steering. To maximize the scan range with minimum number of antennas (M), the solution of the disk covering problem is employed to find initial positions of the feed antennas. A new design procedure is developed to maximize the scan range and reduce side lobes with systematically employed 3D full-wave simulation based parametric sweeps on lens geometry and feed antenna positions. Compared to the conventional planar phased array antenna occupying the equivalent aperture ($L * M$ elements), the presented antenna utilizes a single phase shifter per lens (L) to reduce the hardware complexity. It is demonstrated that the presented antenna performs with the largest scan range and low side lobe level (SLL) compared to previous subarray-based antenna arrays. Specifically, the antenna operates at 38 GHz with $L = 7$, $M = 17$ and provides 12.8% $S_{11} < -10$ dB, 19.8 dBi peak realized gain, a scan range of 80° and SLL below -9 dB.**

Keywords*— *beam steering, mm-wave, phased arrays, lens array

I. Introduction

Recently, a mm-wave beam steering antenna array concept was introduced based on lens antenna subarrays (LASs) [1]. The antenna reduces the hardware complexity since the number of phase shifters needed to support a total of N antennas within a traditional subarray is reduced by a factor of L that represents the number of lenses. Each LAS is fed by $M = N/L$ feed antennas. Excitation of a feed antenna (through the employment of an SPMT switch network) results in a radiated beam steered based on the relative position of the excitation on the focal plane. A single phase shifter per lens is utilized to properly sum the radiated field of each LAS in the far field to create the highest possible antenna gain. The beam steering performance of the antenna can be predicted from array theory by multiplying the single-lens pattern (i.e. pattern of the LAS) with the array factor of the secondary array (i.e. array of LASs). Since the secondary array factor exhibits grating lobes, the radiation performance of the LAS is critical for minimizing side lobe level (SLL) and maximizing the scan range of the entire array.

Although dividing a large phased antenna array into subarrays for reducing the total complexity of the back-end electronics is a well-recognized concept [3], the LAS-based antenna achieves a significantly improved scan range due to the beam steering ability of its subarrays. Reference [1] demonstrates this concept with extended hemi-cylindrical slab lenses and achieves 1D beam steering with -9.4 dB SLL and ±37.5° scan range. This paper extends this concept for 2D beam steering for the first time by developing a LAS-based antenna utilizing extended hemispherical lenses [2]. The design approach followed in [1] focuses on maximizing broadside gain of the LAS. This method, when applied to the 2D LAS design, does not provide the best possible performance. Therefore, a systematic design approach is developed to simultaneously account for gain, SLL, and scan range performances for the 2D beam steering LAS-based antenna design.

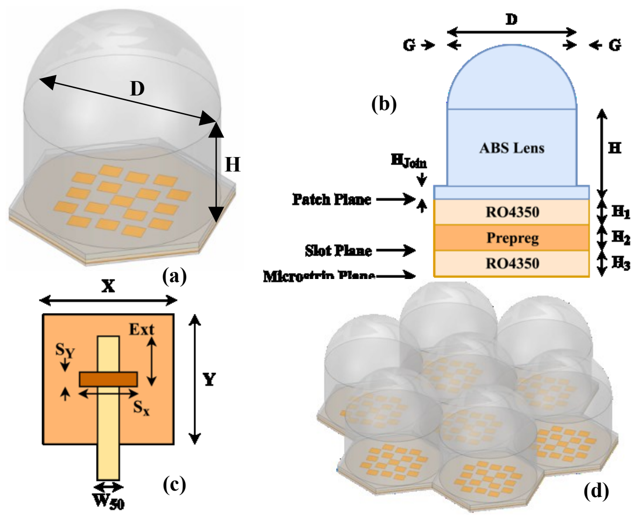

Fig. 1. (a) LAS design with feed antennas; (b) Cross section of the material stack-up (D=15.8, G=0.1, H=8.9, H_{Join}=0.5, H_1=0.305, H_2=0.1, H_3=0.203); (c) aperture coupled feed patch antenna (X=1.4, Y=1.65, S_X=1.4, S_Y=0.11, Ext=0.55 ,W_{50}=0.4); (d) $L = 7$ LAS-based antenna. All dimensions are in mm.

II. 2D LAS-Based Antenna Design

The dielectric slab lenses utilized in recent work [1] exhibit their maximum side lobes in the scanning plane and the analysis becomes straightforward through observing an elevation plane radiation pattern in a single azimuth cut. However, exciting extended hemispherical dielectric lenses with off-axis feed antennas may generate maximum side lobes in arbitrary azimuth cuts. This greatly increases the difficulty of evaluating the performance of the LAS with classical E and H-plane patterns. Another difficulty in the design of a 2D LAS-based antenna is associated with the positioning of the feed antennas in the focal plane. The half power beamwidth (HPBW) of these patterns form contours and typically attain an elliptical shape as the elements are positioned further away from the lens axis. Minimizing the number of feed antennas within a LAS implies determining the antenna positions in the focal plane that will

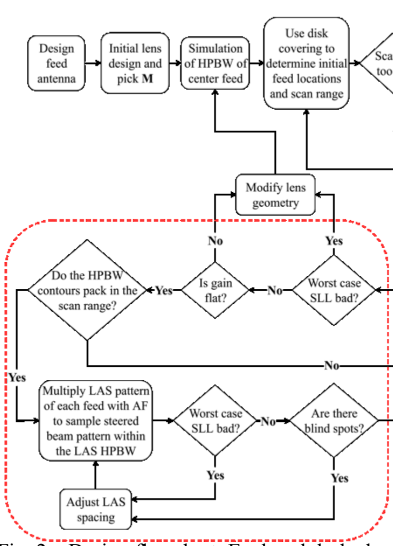

Fig. 2. Design flowchart. Enclosed dashed section employs Julia scripts to generate/process data.

cause these contours to minimally overlap in a way to maximize the coverage of the desired scan range. The HPBW contours can be plotted in the polar plane where the radial axis is used to represent the elevation angles. In this polar plane, the problem becomes similar to the well-known 'disk covering problem' since we attempt to maximize the scan range of M antennas by most optimally arranging their locations (and therefore their HPBWs) to *completely* cover the largest area possible within the polar plane.

To address these challenges, a systematic design strategy is introduced as outlined by the flowchart shown in Fig. 2. The design flowchart is complemented with Julia programming language scripts developed in house to provide visualizations of the HPBW contours and assess the critical performance metrics such as SLL and scan range. Feed antennas are designed as in [1]. Ansys HFSS is used for all full-wave simulations. The diameter of the lens was determined initially as 16 mm to replace an aperture area that would correspond to a M=16 (i.e. 4×4) element half-wavelength spaced phased array at 38 GHz. The diameter of the HPBW contour of the center feed antenna is used to determine the maximum possible scan range via the solution of the disk covering problem assuming all feeds have a similar contour size. This analysis is performed iteratively as to determine the final number of feed antennas along with their initial positions which turns out to be M=17 for this design. All feed antenna patterns are exported, plotted, and analyzed for SLL, gain variation, and scan range coverage quality. Slight updates were made in lens dimensions and feed antenna positions to improve the performance. Once the LAS design is completed, an antenna consisting of 7 LASs is investigated. As shown in the flowchart, slight adjustments are made in the LAS spacing to improve the antenna radiation characteristics. Further details of the design approach will be provided in the conference. Fig. 1 reports all critical dimensions. Fig. 3(a) shows the HPBW contours of the M=17 element LAS. Fig. 3(b) shows representative HPBW contours of the LAS-based antenna with L=7. It is important to note that the LAS-based antenna can generate infinitely many beams and the presented ones are selected to show the full-coverage of the scan range.

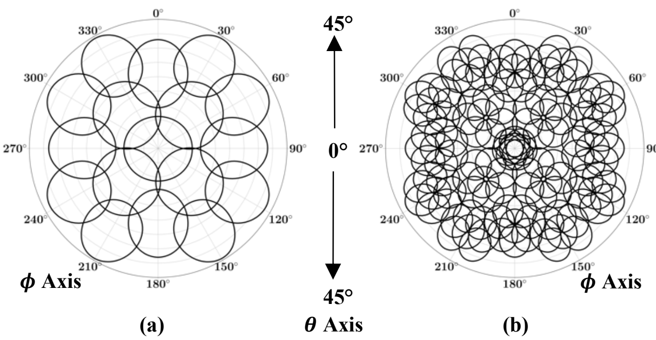

Fig. 3. (a) HPBW contours for M=17 LAS design; (b) Representative HPBW contours for LAS-based antenna with L=7 and M=17.

III. Performance and Concluding Remarks

The feed antenna operates across 37 GHz to 40 GHz with $|S_{11}| < -10$ dB bandwidth. The SLL is determined to be less than -9.7 dB inside the scan range. The SLL is less than -8 dB when all elevation angles are considered. Side lobe radiation in high elevation angle (i.e. close to horizon) is due to the characteristics of the utilized lens. Alternative lenses should be investigated in the future to understand whether the SLL can further be reduced. The scan range of this LAS-based antenna is ±40°. In certain azimuth cuts, the scan range approaches to ±45°. Nevertheless, it is important to note that the presented performance is the best among the subarray techniques reported in literature as shown in Table I. Particularly, the scan range is significantly enhanced due to the lens-based approach while the SLL is kept comparable. Experimental verification is underway and will be reported in the conference.

TABLE I. Arrays with Reduced # of Phase Shifters (PS)

Ref	Tech.	N	M	Freq (GHz)	# of PS	Scan Range	SLL (dB)	HPBW (deg)
[4]	Random	30	-	7.9	12	±14°	-15	4.1°
[3]	Overlap	80	20	10	4	±10°	-19	7°
[5]	Vector Sum	8	4	12.6	10	±18.5°	-9	14.8°
[1]	LAS, 1D	20	5	38	4	±37.5°	-9.4	5.2°
This Work	LAS, 2D	119	17	38	7	±40°	-9.7	10°

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