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140 GHz Wide Scan Lens Antenna Design

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***Abstract* — We introduce the design of an array-fed dielectric lens antenna that enables electronic beam steering within a large Field of View (FoV). The feed array consists of eight cavity-backed double-slot antenna elements, fed by a microstrip feed structure that tilts the beam of each double slot toward the lens center. The slots are loaded with a two Artificial Dielectric Layers (ADL) to increase the front-to-back ratio. The elements are placed closer to the lens surface with respect to the nominal focal plane and are combined with proper weights to reduce the scan loss. Metallic reflectors are positioned along the sides of the array edges to further improve the scanning performance, especially at large scan angles. Full-wave simulations show that the designed antenna realizes a stable gain around 20 dBi within a ±50° FoV coverage, for a lens diameter of 5 wavelengths.**

***Keywords* — double slot, focal plane array, lens antenna, wide scanning.**

I. Introduction

Recent advancements in high-speed millimeter-wave wireless communication and high-resolution radar systems have heightened the demand for lens antennas with high gain and quasi-optical beamforming capability [1]. Multiple beams can be generated simultaneously by positioning multiple feeds within the lens's focal plane. A common example is the elliptical dielectric lens antenna [2], [3], which is simple to design and fabricate and can be conveniently integrated with a planar feed array.

Despite the mentioned advantages, array-fed lens antennas exhibit limitations in terms of scan range and field of view (FoV) coverage. When the feed element in the focal plane array is displaced from the lens axis, large scan loss occurs, due to spillover, phase error, and reflections at the lens-air interface. Moreover, by switching between elements in the array, only a finite number of beams is obtained each pointing in a specific direction, thus the FoV is not covered by a continuous scanning beam.

Methods to extend the scan range of lenses have been proposed, e.g. by altering the feed to tilt the beam towards the center of the lens [4]-[6], by using double lens configurations [7], [8], or by shifting the feed array above the lens focal plane [9]. Although improved scan performance is obtained, none of these solutions was shown to reach an angular coverage exceeding ±45° scan range.

In this work, we aim at achieving a FoV of ±50° with a moderate gain (5-wavelength diameter lens). A plastic lens is considered for its low-cost and low-loss properties [8]. The elements of the feed array are chosen as cavity-backed double-slot antennas, since they can provide efficient illumination of the lens [10]. The array elements are not used individually, but

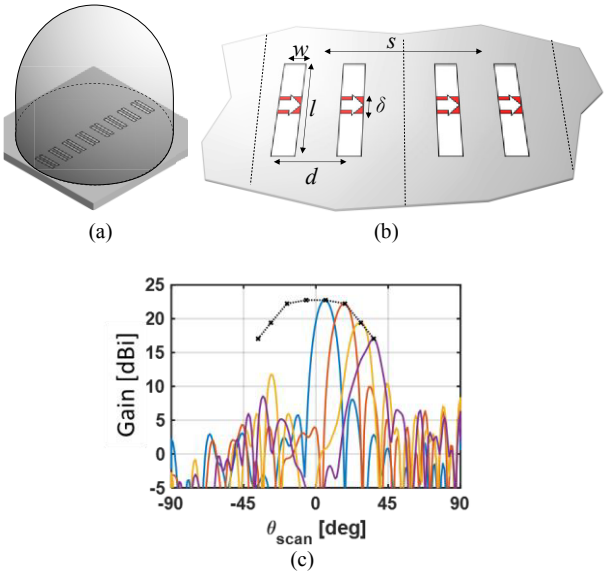


Fig.1 (a) Elliptical lens fed by an eight-element cavity-backed double-slot array, (b) array geometry, and (c) antenna gain over scan angle, when switching between the elements.

combined with proper complex weights to efficiently illuminate the lens and to achieve continuous scanning within the FoV [11]. These weights can be chosen by studying the problem in reception under plane-wave incidence and by applying the field matching technique. We also implement several techniques to reduce scan losses: the beam from the double-slot feeds is tilted towards the center of the lens to improve the radiation efficiency; the feed array is shifted above the nominal focal plane to reduce gain variation withing the FoV; vertical metallic reflectors are used close to the array edges to further increase the scan range.

An in-package implementation of the double-slot array is designed and investigated with simulations, for frequencies around 140 GHz. The resulting design achieves a nearly flat gain around 20dBi within a ±50° FoV.

II. Optimization of the Lens Scan Performance

The design contains an elliptical plastic lens (with relative permittivity of $\varepsilon_r = 2.34$) fed by an array of eight cavity-backed double-slot antennas, as shown in Fig. 1(a). The lens is assumed to be $5\lambda_0$ in diameter, where λ_0 is the wavelength at the calculation frequency f_0. Firstly, the feed array is studied using an in-house spectral domain method of moment (MoM). The MoM provides the mutual impedances of the array and the

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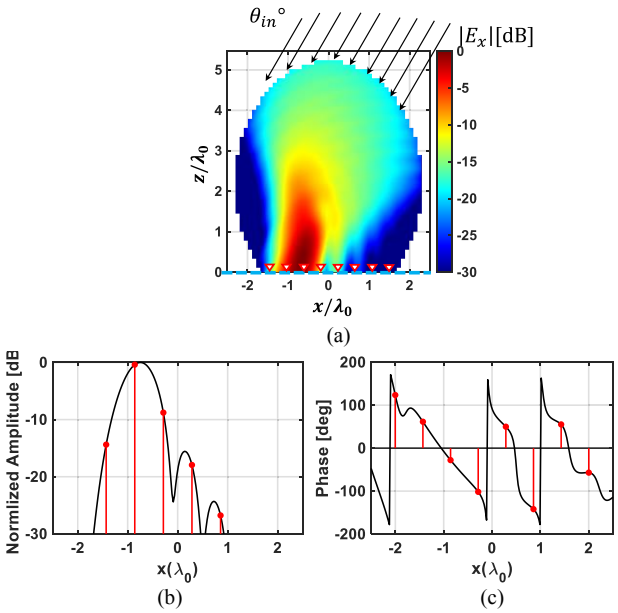


Fig. 2 The x-component of the electric field computed from the problem in reception: (a) magnitude on x-z plane, (b) magnitude on the array plane, and (c) phase on the array plane.

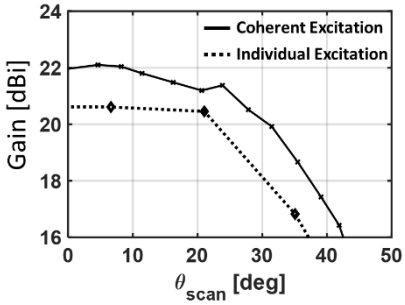


Fig. 3 Comparison of scan loss when the feed array is excited individually (dashed), and coherently (solid).

radiated fields inside the lens. These fields are then used in combination with a geometrical optics (GO) and physical optics (PO) method to compute the far-field radiation patterns outside the lens [10].

The slot array is characterized by the geometrical parameters described in Fig. 1(b). The parameters are chosen as feed length $\delta = 0.1\lambda_0$, slot width $w = 0.08\lambda_0$, slot length $l = 0.73\ \lambda_0$, slot separation in each double-slot element $d = 0.28\lambda_0$, and inter-element spacing $s = 0.57\lambda_0$. Assuming that the elements are excited individually, the resulting gain as a function of the scanning angle at f_0 is reported in Fig. 1(b). It is seen that the antenna gain is reduced by 6 dBi when switching from element 4 to element 1, corresponding to a maximum scanning angle of $\pm 36°$.

A method to improve the scanning range is to vertically displace feed array above of the focal plane of the lens, allowing the array to couple more power from the plane waves that come from large incident angles [12]. However, this implies a gain reduction at broadside, since the array is no longer at the focal plane of the lens. In this design, the array is assumed to be one wavelength above the nominal focal plane of the lens.

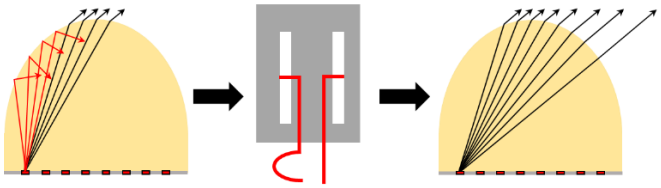


Fig. 4. Beam tilting of the edge element by means of unbalanced transmission lines

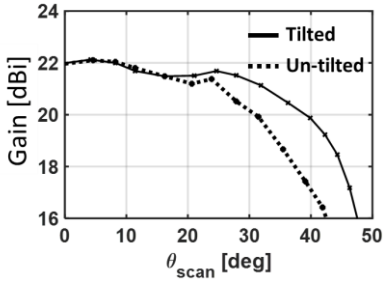


Fig. 5. Comparison of scan loss when the elements of the array are not tilted (dashed) and tilted (solid).

A. Field Matching

The gain reduction can be partially compensated by coherently exciting multiple elements with a proper amplitude and phase distribution. For each pointing angle, the complex weights of the elements are chosen to match the electromagnetic field distribution that would be obtained on the array plane if the lens was illuminated by a plane wave incident from the same angle.

An example on how to calculate the complex weights is shown in Fig. 2. Suppose the target scanning angle is θ_{scan}, we consider a problem in reception where a plane wave is assumed to impinge on the lens from $\theta_{\text{in}} = \theta_{\text{scan}}$. The fields inside the lens for such a problem can be solved with the GO/PO method mentioned earlier. Fig. 2(a) shows the magnitude of the x-component of the electric field on the X-Z plane of the lens for a plane wave impinging from $\theta_{\text{in}} = 15°$. Both the amplitude and the phase of the x-component of the electric field is then sampled based on the elements' position, as shown in Fig. 2(b) and (c). The complex weights to coherently excite the elements are chosen as proportional to the conjugate of the x-component of the electric field.

This technique, also known as the "field matching" method [11], not only helps to compensate the gain drop due to the off-focus effect, but also enables scanning to intermediate scanning direction, as illustrated in Fig. 3.

B. Tilted Element Pattern

Another factor contributing to the gain drop at large scanning angles is that a significant amount of the power radiated by edge elements of the array illuminates the side of the lens surface, causing high reflection and spillover losses. To mitigate this effect, the two slots in each of the elements are fed with lines of different length to implement a phase shift, as depicted in Fig. 4, such that their beams are tilted toward the center of the lens. This approach reduces the amount of radiated

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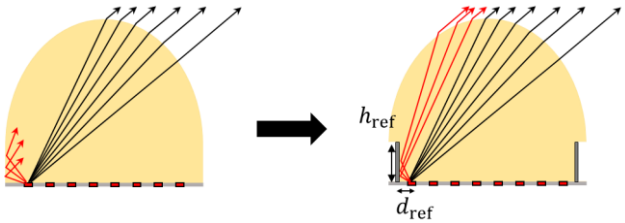


Fig. 6. Reflector at the edge of the array to redirect the sidelobe of the edge element towards the main beam.

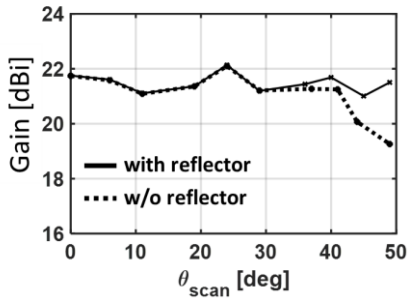


Fig. 7. Comparison of scan loss with and without the edge reflector.

power that enters the critical angle region, and thus improving the overall gain of the antenna, especially considering the edge elements. The effect of the beam tilting is shown in Fig. 5, where it can be seen that the antenna gain is increased by more than 2 dBi at larger scanning angles, compared with the non-tilted case.

C. Edge Reflector

Finally, the radiation efficiency of the edge elements can be further improved by placing a vertical reflector close to the edge of the array. In this way, the power from the sidelobes of the edge elements will be redirected toward the top of the lens and used for radiation, as illustrated in Fig. 6. The array-fed lens antenna is simulated using commercial simulation software CST for the cases with and without reflector at the edge of the array. The addition of the reflector gives a further improvement of antenna gain by 2dBi at the largest scanning angle, as shown in Fig. 7.

The optimized structure achieves a coherent scanning capability until $\pm 50°$, with almost a constant gain.

III. Antenna-In-Package Implementation

A. Array Design

The feed array is designed using multi-layer package technology, as shown in Fig. 8, for different element designs. Firstly, a two artificial dielectric layers (ADLs) made of square sub-wavelength metal patches are placed above the slot plane. The ADLs increases the front-to-back ratio of the antenna and enhances the impedance matching bandwidth by acting as a quarter-wavelength impedance transformer. For the edge elements, metal walls are placed on the side of the ADLs to implement part of the edge reflector described in Sec II.C.

The two slots in the element are fed with unbalanced differential microstrip lines, which are merged to a single-ended

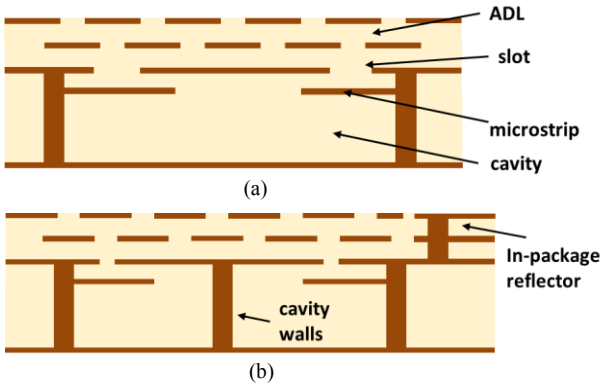
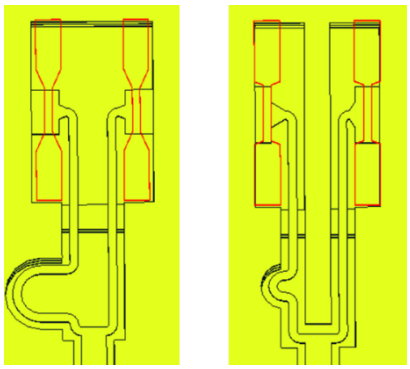


Fig. 8. Vertical cross-section of the (a) central elements, and (b) edge elements



(a) (b)

Fig. 9. Feeding network of the (a) central elements, and (b) edge elements

line outside the cavity. By manipulating the length difference between the unbalanced lines, we can control the phase shift between the two slots, and thus steering the beam of different elements. Fig. 9(a) shows the feeding network for the central elements that does not have a tilted beam. In this case the line length difference implements 180° phase shift (balun) so that the two slots are fed in phase. In Fig. 9(b), the feed of the edge element is depicted, which implements a 60° phase shift between two slots to tilt the radiated beam.

Each double-slot element is backed by a rectangular cavity, to improve the radiation efficiency and reduce the mutual coupling. It is important to note that, to prevent the microstrip feed structure from exciting cavity modes in the edge elements, another via wall is placed in the center of the cavity to separate the lines.

B. Simulated Performance

The entire array-fed lens is simulated in CST frequency domain solver. Fig 10 shows the reflection coefficients of feeding ports from 1 to 4 (as the other four ports are identical to their symmetrical counterparts) for a normalization impedance of $Z_0 = 30\Omega$. It is seen that the elements are impedance matched ($|S_{\mathrm{nn}}| < -10\mathrm{dB}$) within the desired frequency band. To steer the beam of the lens antenna, the elements are combined using proper weights that are obtained from the previously mentioned "field matching" method. Fig. 11 shows the gain patterns when the lens is scanned to 0°, 11°, 22°, 35°, and 50°, respectively. It

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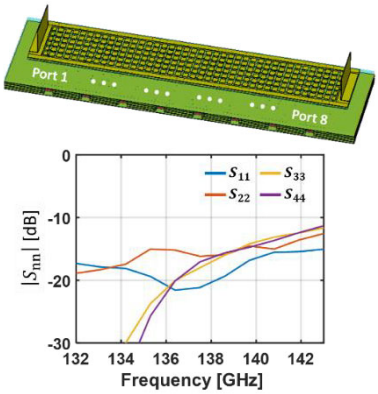
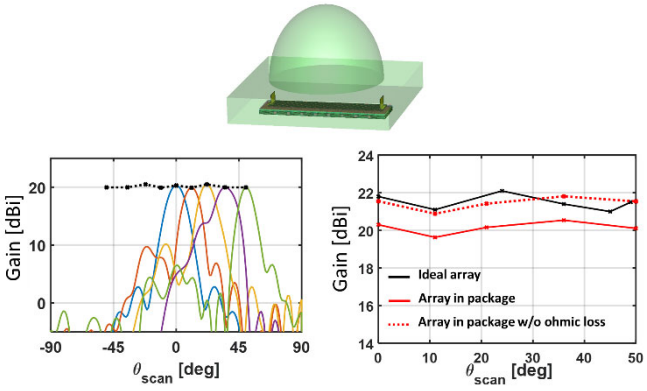


Fig. 10. Simulated reflection coefficients with $Z_0 = 30\Omega$.



(a) (b)

Fig. 11. (a) Simulated gain patterns of the entire array-fed lens for scanning angles at 0°, 11°, 22°, 35°, and 50°, and (b) gain comparisons for ideal array, array-in-package, and array-in-package without ohmic losses.

is seen that the antenna is able to reach a ±50° FoV, with a stable gain around 20 dBi. The simulated ohmic losses from the feeding network are around 1.5 dB. These losses emulate a scenario where the die is present.

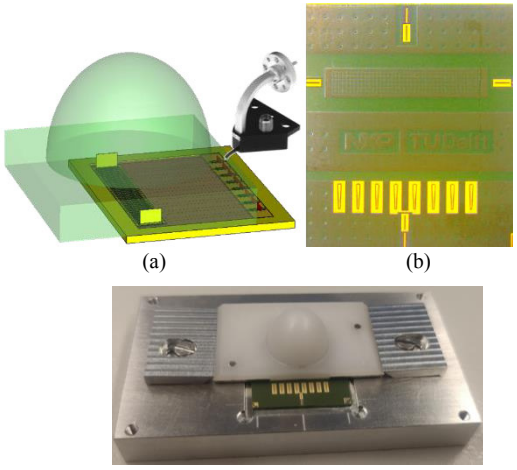
A transition was designed to access the antenna from the top of the package and outside the lens, for measurement purposes, as illustrated in Fig. 12(a). The fabricated package and the complete antenna assembly are shown in Fig. 12(b) and (c).

IV. Conclusion

We presented the design of a wide scanning array-fed dielectric antenna at 140 GHz. The antenna consists of a five-wavelength elliptical plastic lens, fed by an eight element cavity-backed double-slot array, which are implemented using in-package technology. A number of techniques were employed to reduce scan loss and enhance the angular coverage. Simulation results are presented to assess the performance of the lens design. Stable gain of 20 dBi is obtained for scanning up to 50°. A prototype is manufactured and will be tested in the next months. Measured results will be likely available by the time the conference is held and will be presented then.

Acknowledgment

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(a) (b)

(c)

Fig. 12. (a) Antenna measurement setup with transitions extending beyond the lens, (b) fabricated antenna-in package with transitions, and (c) complete antenna assembly.

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