Proof of Concept of a Low-cost Beam-Steering Hybrid Reflectarray that Mixes Microstrip and Lens Elements Using Passive Demonstrators

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***Abstract*—In this article, a proof-of-concept study on the use of a hybrid design technique to reduce the number of phase shifters of a beam-scanning reflectarray (RA) is presented. An extended hemispherical lens antenna with feeds inspired by the retrodirective array is developed as a reflecting element, and the hybrid design technique mixes the lenses with the microstrip patch elements to realize a reflecting surface. Compared to the conventional designs that only use microstrip antennas to realize a reflecting surface, given a fixed aperture size the presented design uses 25% fewer array elements while shows comparable beam-steering performance. As a result of using fewer elements, the number of required phase shifters or other equivalent components such as RF switches and tunable materials is reduced by 25%, which leads to the reduction of the overall antenna system's complexity, cost, and power consumption. To verify the design concept, two passive prototypes with a center frequency at 12.5 GHz were designed and fabricated. The reflecting surface was fabricated by using standard PCB manufacturing and the lenses were fabricated using 3D printing. Good agreement between the simulation and measurement results is obtained. The presented design concept can be extended to the design of RAs operating at different frequency bands including millimetre-wave frequencies with similar radiation performances. The presented design method is not limited to the microstrip patch reflecting elements and can also be applied to the design of the hybrid RAs with different types of reflecting elements.**

I. Introduction

REFLECTARRAYS (RAs) have received significant amount of research interest recently, including the applications for 5G massive MIMO [1], [2] and 6G reconfigurable intelligent surfaces (RISs) [3], [4]. RAs combine the advantages of reflector antennas and phased arrays. A conventional microstrip RA consists of a printed array illuminated by at least one feed such as a waveguide antenna. Each radiating element is designed to provide a pre-adjusted phase to form a focused beam to the desired direction. At its operation frequencies, a RA surface can substitute the traditional parabolic reflector with a lightweight planar structure. To enable an RA with continuously beam-scanning capability, similar to the traditional phased arrays, phase shifters need to be used to control the phase of each reflecting element.

Having low-cost array antennas with good beam-steering capability is highly desirable for modern wireless communications. The largest part of the cost of an electronically beam-scanning array antenna systems is the monolithic microwave integrated components (MMICs). At mm-wave frequency, the costs of the RF components are much higher than microwave components. Thus, with fixed aperture size, if the number of the antenna element can be decreased, the number of phase shifters and associated electronic components will be reduced, then the overall cost of the antenna system is reduced. In the literature, there are studies on reducing the number of antenna elements for an array antenna without decreasing the aperture size. One approach is to increase the distance between the neighbouring antenna elements, as far as the grating lobe would not appear when the beam of the array is scanned in the required angular range [5]. For example, a 16×16 array was reported in [6], where high directivity horn antenna was used as the array element and the distance between the elements was increased to $0.87\lambda_0$, where λ_0 is the wavelength in free space at the center frequency. Due to the use of narrow beamwidth antennas as the array elements, the beam-steering angular range of the array is limited. Another approach is to use the sparse array technique. The sparse array uses aperiodically antenna elements and by synthesising the phase distribution, beam-steering with relatively low sidelobes can be obtained [7], [8]. The challenge for this approach is that not all the elements are radiating simultaneously, which leads to low aperture efficiency. Instead of reducing the array element number, another method is subarray technique. Using the concept of subarray, several antennas or metasurface elements are grouped as a subarray. In this way, the total number of modules required to control the array is less than the total number of array elements. Yet, one problem with this technique is that the resulted array has limited control over the waveform of the radiated signal or requires a closer spacing between the array elements, which may not be feasible for a general array configuration [9], [10]. By randomly group the subarrays, a recent study [11] shows that the number of phase shifters of a phased array can be reduced but the obtained beam-scanning angle range is small.

The objective of this study is to investigate a feasible approach to design a RA of reduced antenna elements while maintaining promising beam-scanning performance. When the beam-forming of a RA is adaptively optimized, fewer reflecting elements means fewer parameters for the optimization matrix, which reduces the computation time and resources. Fewer reflecting elements also means the antenna system will use fewer RF chains. As a result, the outcome of such a technique would lead to a reduction in the overall cost, power

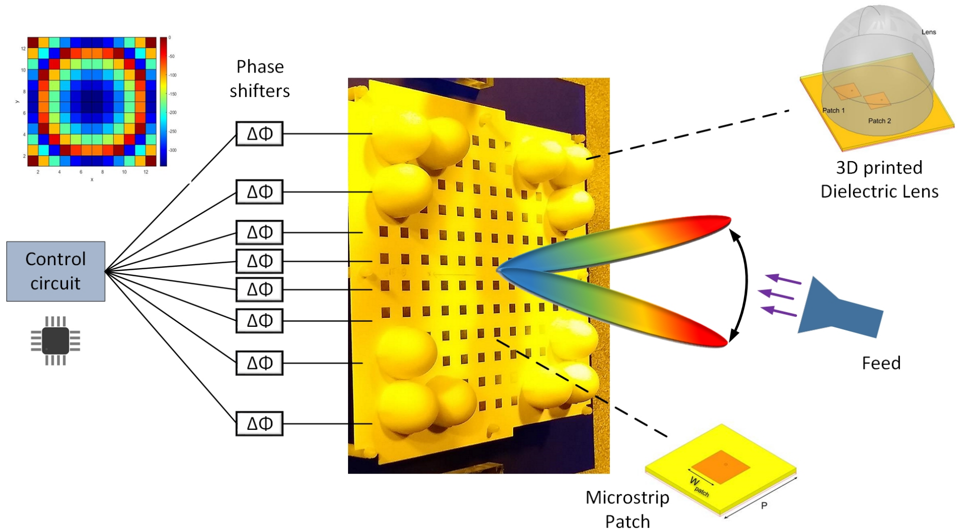

Fig. 1. The concept of the developed hybrid reflectarray with reduced number of array elements.

consumption, and system complexity of the antenna system without sacrificing its beam-scanning performance, which is an improvement compared to other reported methods. Microstrip type RA is chosen for this study due to its wide application in wireless communications. Be noted that the developed design concept is not limited to the microstrip patch reflecting elements and can be applied to other types of RA elements as well. This paper is organized as follows. The hybrid design concept is elaborated in Section II. Then, the design and working principles of the RA elements are presented in Section III. Section IV presents the EM simulation and measurement results of the developed hybrid RA. At the end of the article, some discussions are presented.

II. Hybrid Design Concept

Fig. 1 shows the concept of the developed hybrid RA with a photo of the prototype. As shown, the reflecting surface has two different types of unit cells, microstrip patch and dielectric lens. The patches are printed on a dielectric substrate and were manufactured using PCB technology. The dielectric lenses, which have simple shapes and were fabricated through low-cost 3D printing, are placed at the edge corners of the reflecting surface.

The hybrid design concept is based on the use of lens antenna to replace some of the conventional microstrip patches. In this work, the lens is designed to has a size four times as large as the patch unit cell. Thus, one lens is equivalent to four microstrip patches and the distance between the lenses is larger than one-wavelength. In this case, instead of using four phase shifters, only one phase shifter is required. As a result, the total number of associated RF components is decreased. Because lens has a much narrower beamwidth compared to the microstrip patch, using lens to replace all the patches is equivalent to use high directivity elements as the RA elements. This would constraint the scanning of the RA to a very small angle range. On the other hand, for a RA, similar to the reflector antenna, the reflecting elements at the edge of the aperture are excited with much smaller RF powers compared to the centre elements, which is to reduce the spillover loss. These elements cannot be ignored and still need to be incorporated with the MMICs. Thus, it becomes a feasible approach to use lenses to replace the patches that are positioned at the edge of the reflecting surface. By doing so, the beam scanning performance of the RA will be less affected. To improve the illumination efficiency of the lenses, we developed a new feeding method which is inspired by the retrodirective array. The design details and working principles are presented in Section III. Moreover, by placing the lenses at the edge of the aperture, the periodic boundary condition of the patches is maintained; otherwise the patches would experience impedance mismatching due to the change of the mutual couplings [5] which would affect the radiation efficiency of the RA. As the design and synthesis of the patch and lens elements can be performed independently, as a result, the presented hybrid design approach does not increase the design complexity compared to a conventional design.

To reconfigure the phase of each reflecting element, a phase shifter can be interconnected to each array element. It should be noted that the use of phase shifters is not the only solution to realize phase control, and there are other solutions that can be used to change the phase response of the RA elements such as the using of RF switches and tunable materials [12]. For example, by placing RF switches on the microstrip line of the array element, similar to the design reported in [13], 1-bit or 2-bit phase quantization can be obtained. In this study, the configuration of the developed RA is compatible to be incorporated with these different phase control techniques.

For demonstration purpose, we scaled-down the operation frequency and chose to design a RA operating at the center frequency of 12.5 GHz. Considering the current fabrication accuracy of PCB manufacturing, 3D printing and machining, the presented design can be scaled to operate at mm-wave frequencies. As a proof-of-concept, the prototypes are passive demonstrators and the phase shifters are substituted by microstrip delay lines to mimic the ideal lossless phase shifters. It will be demonstrated that by using the proposed hybrid design method, compared to a regular RA of the same aperture size, the presented design uses 25% fewer elements but with a comparable gain and beam-steering performance.

III. Element Design

The microstrip patch unit cell is a probe-fed patch and the patch is designed to have a center frequency at 12.5 GHz. Fig. 2 shows the configuration of the patch antenna. The patch is printed on a 0.5 mm thick RO4003C substrate ($\varepsilon_r = 3.55$, $tan(\delta)$=0.0027). RO4003C substrate is chosen in this study due to its advantages of good mechanical strength, low loss and stable permittivity. The period (P) of the unit cell is 15 mm, which is about $0.625\lambda_{12.5GHz}$. The width (W_{Patch}) of the square patch is 5.9 mm. The phase shifter is placed on another 0.3 mm thick RO4003C. A 0.1mm thick pre-peg (ε_r =3.54) is used to bond the two substrates. A clearance hole is etched on the ground plane through which a via is used to connect the patch and the microstrip line that is interfaced with the phase shifter. The working principle of this patch element is that the patch receives the incident wave and then converts the RF signal into the electrical current. The electrical current then transmits to the phase shifter through the interconnections. After adding some phase shifts from the phase shifter, the signal re-transmits to the patch and the patch re-radiates. In this way, by controlling the phase shifter, the patch radiates with a controllable phase. The simulation results show that the loss of this passive element is less than 0.5 dB at the frequencies of interests.

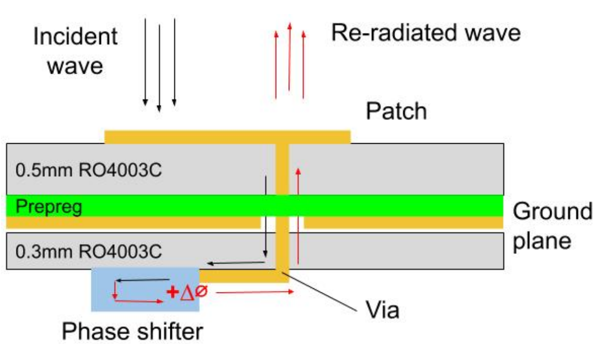

Fig. 2. The configuration and working principle of the microstrip patch element for the reflecting surface.

Fig. 3 shows the configuration of the lens antenna. As the lenses are to be placed at the edge of the reflecting surface while the beamwidth of a lens is narrow, the lenses would receive very low RF power when the incident wave is from large angles. As a result, the illumination efficiency of the RA would be low. To mitigate this issue, inspired by the retrodirective array [14], a pair of patches with a connected feed line are innovatively used as the feeding sources of the lens. The two square patches are probe-fed and have the same configurations as the microstrip patch element presented above except that the two patches are connected to each other through a 50Ω microstrip printed at the bottom layer. The width of the square patch is 5.4 mm. Patch 2 is positioned at the center of the lens while Patch 1 is placed at an offset position. With a microstrip line and not taking account of the loss of the phase shifter, the transmission loss between Patch 1 and 2 is less than 0.2 dB. The lens is an extended hemispherical lens. The material of the lens is Polytetrafluoroethylene (PTFE) (ε_r =2.2, $tan(\delta)$=0.001) and the dimensions of the extended hemispherical lens are calculated using the formulas given in [15]. The lens has a simple cylindrical shape and it can be easily fabricated by machining with low-cost.

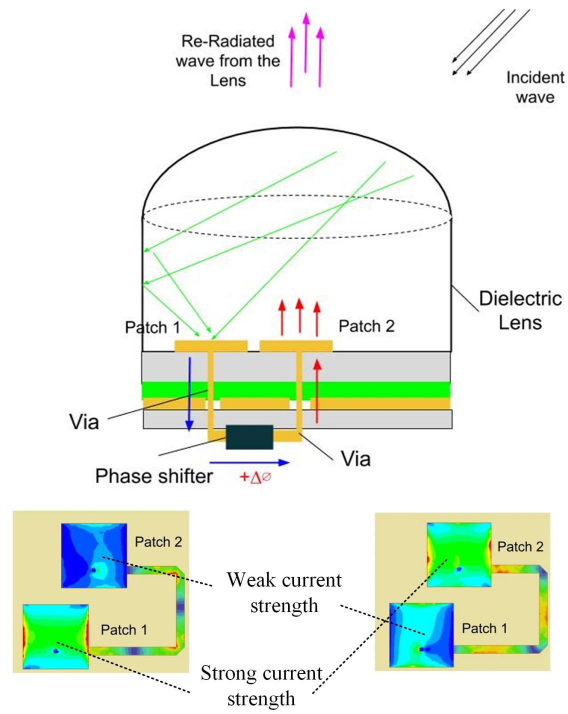

Fig. 3. The configuration of the lens antenna and its working principle. The figures in the bottom are extracted on two different time nodes, which demonstrate that Patch 1 receives the RF signals from the feed and then the electrical signal transmits to Patch 2 for re-radiation. The lens has a diameter two times as large as the period of the patch elements and two patches are placed under the lens.

The working principle of the lens antenna element is as follows. In this work, the RA is centre-fed so the incident wave is pointing at the center of the reflecting surface and at the edge of the reflecting surface, the incident waves come with certain angles (e.g. 40^o). The offset feed patch (Patch 1) generates a tilted beam from the lens so the lens can efficiently receive the incident waves from the feed. After that, the received RF energy is then transmitted to the center patch (Patch 2) with added phase delays from the phase shifter. Then, Patch 2 feeds the lens and generates a high directivity beam in the boresight. To better demonstrate how Patch 1 and Patch 2 operate, Fig. 3 also shows the simulated current distribution on Patch 1 and Patch 2 when the lens is receiving and re-radiating, respectively. This simulation is performed by using a 3-D electromagnetic full-wave simulator. As shown, when the lens is receiving the RF signal from the incident wave, there is a strong current on Patch 1. When the lens is re-radiating, there is a strong current on Patch 2. To improve the illumination efficiency of the lens, the position of Patch 1 needs to be optimized. Patch 1 is located on a circle with a radius of R and an angle of Φ_p relative to Patch 2. These two parameters respectively determine the angles of the title beam (θ_t, φ_t) of the lens. If an offset-fed configuration is used, the position of Patch 1 should be optimized by using the same principle.

Having a low mutual coupling between Patch 1 and Patch 2 is crucial for the presented design because high mutual coupling would affect the re-radiated waveform of the RA. For example, when Patch 2 is radiating, if Patch 1 also gets excited due to high mutual coupling from Patch 2, then unwanted radiation is generated. To ensure that the mutual coupling between Patch 1 and Patch 2 is at least -15 dB, these two patches are placed diagonally, as shown in Fig. 3. This type of configuration means that when Patch 2 is radiating, the beam of the lens antenna will be in the diagonal plane. For this reason, to maximize the efficiency for Patch 1 to receive the incident wave from the feed, the lenses are placed in the edge corners of the reflecting surface, as shown in Fig. 1. In this design, the diameter of the lens is chosen to be 28 mm, which is approximate twice the period of the patch unit cell. The parameters for the lens are $a = 14mm$, $b = 17.3mm$, and $L = 10.2mm$. The distance (R) between Patch 1 and Patch 2 is 8.2 mm $(0.34\lambda_{12.5GHz})$. The results of the EM simulation show that with these parameters when Patch 2 is excited, the lens radiates in the boresight with a gain of 12.8 dBi. When Patch 1 is excited, the beam of the lens titled to 37^o in diagonal plane $(\varphi = \pm 45^o)$ with a gain of 12.5 dBi. The simulated isolation between Patch 1 and Patch 2 is higher than 15 dB.

IV. Reflectarray Design, Simulation, and Measurement

A. Reflectarray Design

To prove the design concept, passive reflectarrays were designed and simulated. At this stage of our study, ideal phase shifters are considered. The lengths of the micrsotrip lines are varied in order to provide different phase distributions of the RA reflecting surface and realize different reflected waveforms.

As mentioned in Section III, to maintain low mutual coupling between Patch 1 and Patch 2, these two patches are placed in a diagonal position. This type of configuration determines that the title beam of the lens antenna (when Patch 1 is radiating) is in the diagonal plane. Thus, for higher illumination efficiency the lenses are placed at the four corners of the aperture. The designed RA is equivalent to a conventional patch-only reflecting surface with 12×12 elements. The size of the reflecting surface is 180 mm×180 mm $(7.5\lambda_{12.5GHz} \times 7.5\lambda_{12.5GHz})$. Compared to the conventional RA, the twelve patches in each corner of the aperture are replaced by three lenses. Thus, with the same aperture size, instead of using 144 elements, the presented design uses 108 elements, corresponding to 25% reduction of the array elements.

To check the beam-scanning performance of the hybrid RA, four passive RAs are designed and simulated, which have the reflected beam pointing at elevation angles of 0^o, 10^o, 20^o, and 30^o in the E-plane $(\varphi = 0^o$ plane), respectively. These RAs have the same configuration and the only difference is the phase delays added to the reflected signal.

B. Simulation Results

Fig. 4 shows the simulated far-field radiation patterns of the designed RAs in the E-plane when the reflected beam is pointing at different angles, including $(\theta = 0^o, \varphi = 0^o)$, $(\theta = 10^o, \varphi = 0^o)$, $(\theta = 20^o, \varphi = 0^o)$, and $(\theta = 30^o, \varphi = 0^o)$. In the EM simulations, a microstrip line of varying lengths is used to adjust the reflected phase of each array element, representing the case that an ideal lossless phase shifter is employed. The RA is centre-fed and the feed is a circular waveguide antenna with a gain of 14 dBi at 12.5 GHz. This circular waveguide antenna is placed 120 mm above the center of the reflecting surface.

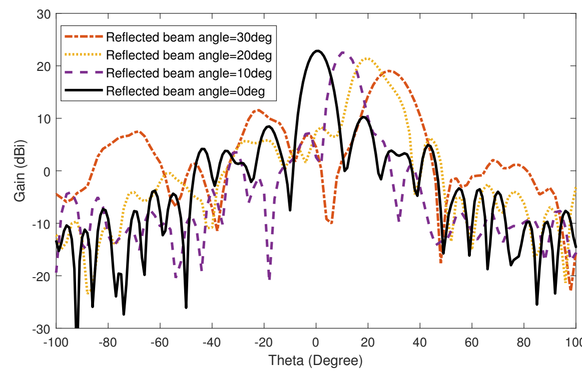

Fig. 4. The simulated beam-scanning performance of the developed hybrid RAs. When the beam points to 20^o, the gain drop is 1.5 dB. When the beam is steered to 30^o, there is a 3.9 dB gain drop. Detailed parameters of the radiation patterns are listed in Table I.

In order to compare the performance of the developed hybrid reflecting surface with the conventional design that only uses patch as the array element, four passive patch-only reflecting surfaces are also designed and simulated. These four RAs have the same aperture size and configuration as the developed hybrid RAs. The radiation performances of these two types of designs at the centre frequency (12.5 GHz) are summarized in Table I. As shown in this table, when configuring the reflected waves to point at different angles, these two types of RAs show similar waveforms. The gain of the hybrid RA is 1.4 dB lower than the patch-only RA when the reflected waveform is directing to 30^o. This is due to the narrow beamwidth of the lens and is a design trade-off. Except for this, with 25% less reflecting elements, the developed hybrid RAs show comparable radiation performances to the conventional patch-only RAs. The simulation results also show that when the RA has the beam pointing at $(\theta = 0^o, \varphi = 0^o)$, the developed RA shows wider 3-dB gain bandwdith than the regular RA.

C. Measurement Results

To validate the radiation performance of the developed RA, two prototypes were fabricated and measured. As a proof of

TABLE I
COMPARISON OF THE PRESENTED DESIGN WITH THE CONVENTIONAL PATCH-ONLY RA WITH BEAM POINTING AT DIFFERENT ANGLES.

	Presented Hybrid RA				Conventional Patch RA				
Beam angle	$\theta = 0^o$	$\theta = 10^o$	$\theta = 20^o$	$\theta = 30^o$	$\theta = 0^o$	$\theta = 10^o$	$\theta = 20^o$	$\theta = 30^o$	$\theta = 0^o$ (corner elements removed)
Aperture size	$7.5\lambda \times 7.5\lambda$	$7.5\lambda \times 7.5\lambda$	$7.5\lambda \times 7.5\lambda$	$7.5\lambda \times 7.5\lambda$	$7.5\lambda \times 7.5\lambda$	$7.5\lambda \times 7.5\lambda$	$7.5\lambda \times 7.5\lambda$	$7.5\lambda \times 7.5\lambda$	$7.5\lambda \times 7.5\lambda$
No. of elements	108	108	108	108	144	144	144	144	96
Gain	22.9 dBi	22.2 dBi	21.4 dBi	19 dBi	23 dBi	22.5 dBi	21.8 dBi	20.4 dBi	21.6 dBi
Half power beamwidth	8^o	8.1^o	11.2^o	13.6^o	8^o	8.1^o	11.3^o	12.8^o	11.5^o
Sidelobe level	15 dB	14.4 dB	13.1 dB	11 dB	11 dB	15.3 dB	16.9 dB	11.4 dB	10.5 dB

concept, instead of using phase shifters, microstrip lines of different lengths were used to mimic the phase shifters and provide required phase distributions. One photo of the prototype is shown in Fig. 1. One prototype has the reflected beam pointing at boresight, and the other prototype has the beam pointing at 20^o in the E-plane. The lenses were fabricated through 3D printing and each of the lenses is attached to the PCB by four screws. Fig. 5 compares the normalized radiation patterns of the measured and simulated results. There is good agreement between the simulations and measurements, which validates the EM simulation models and proves the robustness of the design as well as the assembling method. In order to fix the reflecting surface and the waveguide antenna to the testing platform, some plastic fixing structures were fabricated. The unwanted reflections from these fixing structures have some effects on the sidelobes of the measured radiation patterns. The measured 1-dB gain bandwidth of the proposed RA in the boresight is 3.2%. This value is similar to the conventional patch type RA.

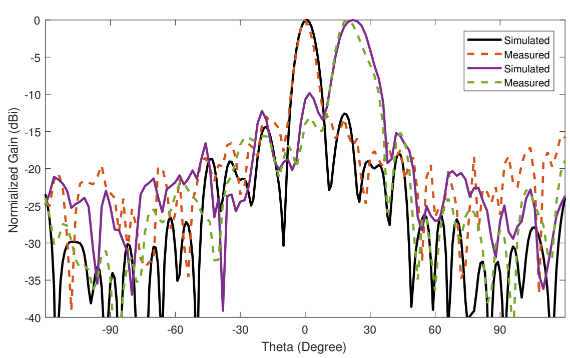

Fig. 5. Comparison of the normalized radiation patterns of the measured and simulated radiation patterns.

V. DISCUSSION

This study is a proof-of-concept for the proposed hybrid design method to reduce the number of elements in a RA with given aperture size. At the current stage of this study, before extending the presented design concept to an electrically reconfigurable RA, we designed, fabricated and measured passive prototypes as demonstrators. During the design of the demonstrators, some assumptions are made which to some extent simplifies the RA element design. In this section, we would like to discuss how to extend the present design concept in our future work.

- **Lens fabrication and assembling**. For the developed hybrid RA, additional lenses are introduced and placed on the top of the PCB. The lens has simple cylindrical form and the material is PTFE. In this study, considering low-volume fabrication, we used 3D printing. The cost can be further reduced if using machining with high quantity production. The assembling of the lenses are performed by using pre-defined holes in the PCB and the lenses. This ensures good alignment accuracy, which can be evident by the good agreement between the presented simulation and measurement results. Thus, the presented design is suitable to be fabricated by a large quantity.
- **All lenses design**. In this study, we chose to replace the patches at the edge corners of the reflecting surface by the lenses for the purpose of maintaining good illumination efficiency of the RA, as the lens antenna has a title beam in the diagonal plane. This limitation is from the consideration of maintaining low mutual couplings between the feed patches of the lens antenna. The use of lens-only to realize a RA would be our future work. To achieve this, we need to investigate the miniaturization of the feed patches and methods to reduce the mutual coupling between the patches.
- **Frequency scalability**. In terms of frequency scalability of the presented design, considering the fabrication accuracy of the PCB technology and the resolution of 3D printing or machining, the developed RA can be scaled to operating in the millimetre frequency range. For Terahertz (THz) design, waveguide antennas would be preferred. Thus, the presented method may not be suitable to be directly extended to the THz RA design.
- **Size scalability**. The reflecting surface can be enlarged by increasing the number of array elements. The first step would always be designing the reflecting surface using the patch-only elements and then using the lenses to replace the microstrip patches at the edge of the aperture. In the presented design, three lens antennas are placed at each

corner of the reflecting surface. When the aperture size of the RA is increased, the number of lenses placed at the corners should also be increased.

- **Beam-forming performance and efficiency**. In this work, we investigated reflecting the incident waves up to 30^o off the boresight. From the simulation and measurement results, the developed hybrid RA shows comparable radiation performance when the reflected waveform is directed within the angle range from 0^o to 30^o. In principle, similar waveforms will be obtained if the reflected waveform is directed within the angle range from -30^o to 0^o. Thus, it can be concluded that the developed hybrid design approach does not compromise the efficiency of the reflectarray if the reflected waves are within the angular range of $\pm 30^o$. For an electrically beam-scanning RA, the lenses can be deactivated if the beam of the RA is require to be scanned to larger angles then the hybrid RA would operate as a conventional patch-type RA. This implies that at large scan angles the efficiency of the presented design would decrease; however, as the RA elements at the edge of the aperture have low excitation amplitudes and considering the intrinsic scan loss associated with the phased array, the reduction in efficiency would be small.

VI. Conclusion

In this article, a hybrid design method to reduce the number of phase shifters in a RA is presented. This method uses both lenses and microstrip patches to realize the reflecting surface, leading to a reduction of 25% of the reflecting elements compared to a regular patch array. With a reduced number of elements, the developed reflecting surface shows similar gain and radiation patterns compared to the patch only RA of the same aperture size when the direction of the reflected wave is steered within the angle range of $\pm 30^o$. This study is a proof-of-concept and passive demonstrators are designed and fabricated to verify the proposed design concept. The presented design has the potential to be extended to a dual-polarized design by using dual-polarized antennas as the reflecting elements of the RA.

References

[1] Y. Hu, W. Hong, and Z. H. Jiang, "A Multibeam Folded Reflectarray Antenna With Wide Coverage and Integrated Primary Sources for Millimeter-Wave Massive MIMO Applications," *IEEE Transactions on Antennas and Propagation*, vol. 66, no. 12, pp. 6875–6882, 2018.

[2] M. H. Dahri, M. H. Jamaluddin, M. I. Abbasi, and M. R. Kamarudin, "A Review of Wideband Reflectarray Antennas for 5G Communication Systems," *IEEE Access*, vol. 5, pp. 17 803–17 815, 2017.

[3] G. C. Alexandropoulos, G. Lerosey, M. Debbah, and M. Fink, "Reconfigurable Intelligent Surfaces and Metamaterials: The Potential of Wave Propagation Control for 6G Wireless Communications," 2020.

[4] L. Dai, B. Wang, M. Wang, X. Yang, J. Tan, S. Bi, S. Xu, F. Yang, Z. Chen, M. D. Renzo, C. B. Chae, and L. Hanzo, "Reconfigurable Intelligent Surface-Based Wireless Communications: Antenna Design, Prototyping, and Experimental Results," *IEEE Access*, vol. 8, pp. 45 913–45 923, 2020.

[5] R. J. Mailloux, *Phased array antenna handbook*. ARTECH HOUSE, INC., 2005.

[6] Y. Li, L. Ge, J. Wang, S. Da, D. Cao, J. Wang, and Y. Liu, "3-d printed high-gain wideband waveguide fed horn antenna arrays for millimeter-wave applications," *IEEE Transactions on Antennas and Propagation*, vol. 67, no. 5, pp. 2868–2877, 2019.

[7] O. M. Bucci, S. Perna, and D. Pinchera, "Interleaved isophoric sparse arrays for the radiation of steerable and switchable beams in satellite communications," *IEEE Transactions on Antennas and Propagation*, vol. 65, no. 3, pp. 1163–1173, 2017.

[8] B. Zhang, W. Liu, J. Ma, Z. Qi, J. Zhang, L. Han, Y. Li, X. Zhao, C. Zhang, and C. Wang, "Sparse antenna array based positional modulation design with a low-complexity metasurface," *IEEE Access*, vol. 8, pp. 177 640–177 646, 2020.

[9] A. Abbaspour-Tamijani and K. Sarabandi, "An affordable millimeter-wave beam-steerable antenna using interleaved planar subarrays," *IEEE Transactions on Antennas and Propagation*, vol. 51, no. 9, pp. 2193–2202, 2003.

[10] J. Zhang, W. Liu, C. Gu, S. S. Gao, and Q. Luo, "Multi-beam multiplexing design for arbitrary directions based on the interleaved subarray architecture," *IEEE Transactions on Vehicular Technology*, vol. 69, no. 10, pp. 11 220–11 232, 2020.

[11] B. Rupakula, A. H. Aljuhani, and G. M. Rebeiz, "Limited Scan-Angle Phased Arrays Using Randomly Grouped Subarrays and Reduced Number of Phase Shifters," *IEEE Transactions on Antennas and Propagation*, vol. 68, no. 1, pp. 70–80, 2020.

[12] Q. Luo, S. S. Gao, W. Liu, and C. Gu, *Low-cost Smart Antennas*. Wiley UK, 2019.

[13] H. Yang, F. Yang, S. Xu, Y. Mao, M. Li, X. Cao, and J. Gao, "A 1-bit 10×10 reconfigurable reflectarray antenna: Design, optimization, and experiment," *IEEE Transactions on Antennas and Propagation*, vol. 64, no. 6, pp. 2246–2254, 2016.

[14] N. B. Buchanan, V. F. Fusco, and M. van der Vorst, "SATCOM Retrodirective Array," *IEEE Transactions on Microwave Theory and Techniques*, vol. 64, no. 5, pp. 1614–1621, 2016.

[15] X. Wu, G. V. Eleftheriades, and T. E. van Deventer-Perkins, "Design and characterization of single- and multiple-beam mm-wave circularly polarized substrate lens antennas for wireless communications," *IEEE Transactions on Microwave Theory and Techniques*, vol. 49, no. 3, pp. 431–441, Mar 2001.

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