Aalborg Universitet

AALBORG UNIVERSITY
DENMARK

A Millimeter-Wave Gain Filtering Transmitarray AntennaDesign Usinga Hybrid-Lens

Mei, Peng; Zhang, Shuai; Lin, Xianqi; Pedersen, Gert Frølund

A Millimeter-Wave Gain Filtering Transmitarray Antenna Design Using a Hybrid-Lens

Peng Mei, *Student Member, IEEE*, Shuai Zhang, *Senior Member, IEEE*, Xian Qi Lin, *Senior Member, IEEE*, and Gert Frølund Pedersen, *Senior Member, IEEE*

Abstract—**This letter proposes a millimeter-wave gain filtering transmitarray (TA) antenna using a hybrid-lens. The hybrid-lens is incorporated by a substrate integrated waveguide (SIW) cavity bandpass filter and a dielectric lens. The dielectric lens serving as a phase shifter is seamlessly coated on the SIW bandpass filter to achieve a co-designed architecture. The proposed hybrid-lens unit cell (UC) is required to not only fulfill the desired phase shifts but also maintain a stable bandpass response, simultaneously. Therefore, the specific shape of the dielectric lens UC must be optimized to minimize its impacts on the bandpass response of the original SIW bandpass filter as much as possible to ensure the filtering performance of the proposed hybrid-lens UC. After some optimizations, the dielectric lens UC based on the air-perforated dielectric square post (APDSP) is determined finally. The simulated results show that the bandpass responses of the hybrid-lens UC are still maintained when the profile of the APDSP-based dielectric lens UC is varied to satisfy a full phase-cycle (2π). The proposed hybrid-lens UCs are arranged reasonably to construct a TA antenna to fulfill the high-gain and gain filtering performance. The simulated and measured results are consistent, revealing the proposed TA antenna has a gain of 25.5 dBi at 35 GHz, and a bandpass gain filtering response over 30 to 40 GHz.**

Index Terms— **High-gain, gain filtering, substrate integrated waveguide (SIW), dielectric lens, air-perforated dielectric square posts (APDSPs).**

I. INTRODUCTION

ATRANSMITARRAY antenna (TA) consists of a feed source and a transmitarray board established by lots of elements. Each element incorporates a certain transmission phase shift to compensate for the different path lengths from the phase center of feed source and then produced a focused beam in a specified direction. Due to the advantages of TA antennas, such as high gain, the simplicity of feed network, easy fabrication, and low cost, they have drawn much attention. Many efforts are devoted to improving and expanding the performance and functions of TA antennas. Multiple layers were utilized to widen the bandwidths of the TA antennas as reported in [1]-[4] by controlling the transmission amplitude variations and phase ranges. Varactors or p-i-n diodes were employed to control the transmission phase of every element individually to obtain a reconfigurable TA antenna for beam-steering applications [5]-[8]. 3-D printed technologies were fully utilized to construct dielectric TA or reflectarray (RA) antennas to simplify the unit cell (UC) design and eliminate conductor loss caused by metallic patterns [9]-[12]. The authors in [13] proposed an antenna with gain filtering performance that realized by covering a substrate integrated waveguide (SIW) cavity frequency selective surface (FSS) with a bandpass response at the aperture of a horn antenna in the microwave band. Therefore, an integrated module with filtering and radiation performance called filtenna is achieved, where the bandpass SIW cavity FSS would shape the gains of the entire antenna according to its frequency response. However, the unavoidable insertion loss of the SIW cavity FSS would cause the gain of the entire antenna smaller than that of the individual source antenna. This kind of filtenna is promising to be implemented in the form of a TA antenna if the desired UC is created. It is required that the desired UC should not only provide a bandpass frequency response but also be easy to achieve a full phase-cycle (2π). Ideally, the control of the transmission amplitude of the desired UC should be independent of its transmission phase as much as possible. By a reasonable combination of an FSS and a dielectric lens, the desired UC fulfilling the aforementioned requirements is expected to be achieved. Specifically speaking, the FSSs provide a bandpass response; and the dielectric lens is imposed to achieve a full phase-cycle (2π). Here, the recombination of the FSS and the dielectric lens is called hybrid-lens in this letter. The hybrid-lens UC must satisfy the following conditions simultaneously: ⅰ). realize a full phase-cycle; ⅱ). maintain the bandpass frequency response that the original FSSs has over the entire phase-cycle. As a result, a TA or RA antenna constructed by the proposed hybrid-lens UCs would achieve a high gain and gain filtering performance.

This letter designs the desired hybrid-lens UC and applies them to achieve a transmitarray antenna with gain filtering performance at a millimeter-wave frequency band. The desired UC is based on SIW bandpass filter and a dielectric lens in a

co-designed architecture, where the dielectric lens is seamlessly coated on the SIW bandpass filter to compensate the required phases for the TA antenna construction. The simulated and measured results are consistent, revealing the proposed TA antenna has a gain of 25.5 dBi at 35 GHz, and a bandpass gain filtering response over 30 to 40 GHz.

II. HYBRID-LENS UNIT CELL DESIGN.

The geometries of the proposed hybrid-lens UC are shown in Fig. 1. The dielectric substrate used here is Rogers 5880 with a thickness of 0.508 mm, a relative permittivity of 2.2, and a loss tangent of 0.009 at Ka-band. It consists of a SIW cavity bandpass filter and a dielectric lens. As is known to all, the SIW cavity as shown in Figs. 1 (a) and (b) can provide a second-order bandpass response. One reflection zero is generated by the slot resonator resonances and the other is attributed to the SIW dielectric cavity resonances. A transmission zero caused by the electromagnetic coupling from upper to lower metallic patch through the SIW dielectric cavity is also expected. The dielectric lens is a good candidate to be served as a phase shifting component due to its easy fabrication and simplicity. For the hybrid-lens UC, it is required that the bandpass response should be maintained when the thickness of the dielectric lens is varied to cover a full phase-cycle. Therefore, the specific shape of the dielectric lens is very important for the hybrid-lens UC design. Much fewer impacts on the response of the original SIW bandpass filter when the dielectric lens is seamlessly coated on the filter as shown in Fig. 1 (c) is preferred. After some optimizations, the dielectric lens UC based on the air-perforated dielectric square post (APDSP) is finally selected to achieve a co-designed architecture together with the SIW bandpass filter. The dielectric material available for the dielectric lens manufacture is with a thickness of t, a relative permittivity of 2.89, and a loss tangent of 0.01 at around 35 GHz.

(a)   (b)
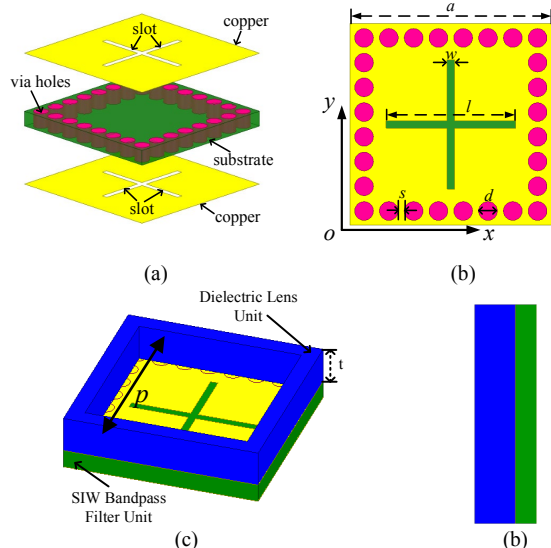

(c)   (b)

Fig.1. Geometries of the proposed hybrid-lens UC. (a). Perspective view of the SIW cavity bandpass filter. (b). Front view of the SIW cavity bandpass filter. (c). Perspective view of the hybrid-lens UC, and (d). Side view of the hybrid-lens UC. (Dimensions: a=5.4 mm, l=3.48 mm, w=0.2 mm, d=0.5 mm, s=0.2 mm, p=4.5mm)

The transmission phase and transmission amplitude of the proposed hybrid-lens UC are then simulated to check its feasibility for the proposed TA antenna construction. All simulations are carried out with High-Frequency Structure Simulator (HFSS) software. Firstly, the transmission phase of the proposed hybrid-lens UC is examined. Due to the highly symmetrical geometry of the proposed hybrid-lens UC, the transmission phase is simulated and presented in one polarization. Based on the APDSP-based dielectric lens, the transmission phase of the proposed hybrid-lens UC can be flexibly controlled by just varying the thickness of the APDSP-based dielectric lens UC with other dimensions of it and the dimensions of the SIW cavity bandpass filter fixed. Fig. 2 (a) shows the transmission phase of the proposed hybrid-lens UC when the thickness of the dielectric lens UC t is varied at 34.5, 35, and 35.5 GHz. It is observed that the transmission phase can cover a full phase-cycle when the thickness t is tuned from 2 mm to 36 mm.
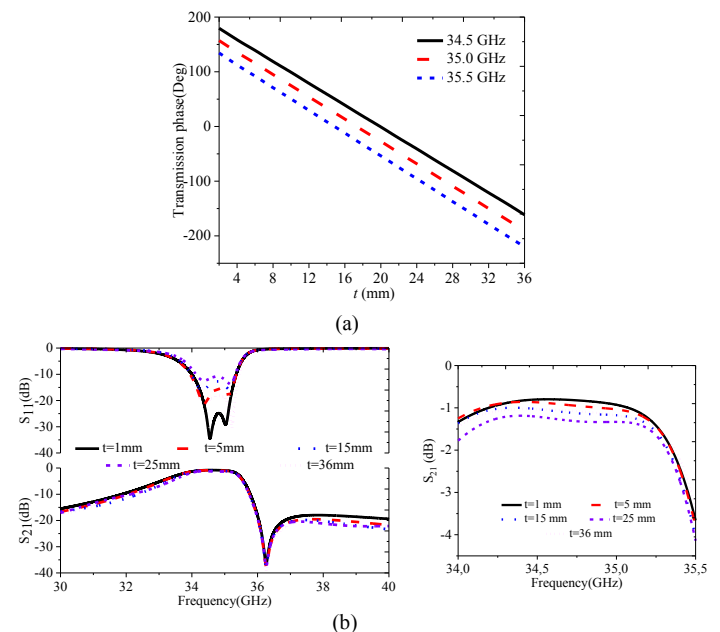

(a)

(b)

Fig. 2. S-parameters of the hybrid-lens UC versus t. (a). The transmission phase of the hybrid-lens UC versus t at 34.5 GHz, 35GHz, and 35.5 GHz. (b). S_{11} and S_{21} of the hybrid-lens UC versus t.

The S-parameter of the proposed hybrid-lens UC is also evaluated. As stated before, the hybrid-lens is required to maintain the bandpass frequency response that the original bandpass SIW filter has within the full phase-cycle. For brevity, some discrete thicknesses are selected (e.g., t=1 mm, t=5 mm, t=15 mm, t=25 mm, t=40 mm) to check the S-parameter of the proposed hybrid-lens UC as presented in Fig. 2 (b). It is found that the bandpass frequency responses of the hybrid-lens UC are still maintained when the thickness t is varied. The extra addition of the dielectric lens UC does not influence the slot and dielectric cavity resonances of the SIW bandpass filter, where two transmission poles within the passband and the transmission zero in the upper band are still observed and maintained. Fig. 2 reveals that the proposed hybrid-lens UC not only owes a bandpass response but also has a full phase-cycle. It indicates that the proposed hybrid-lens UCs are suitable for the proposed

gain filtering TA antenna design.

It should be noted that the shape of the dielectric-lens UC presented here is not the only configuration for the proposed hybrid-lens UC design. From Fig. 2 (a), it is seen that a full phase-cycle (2π) is obtained when the thickness of the APDSP-based dielectric-lens is up to 35 mm. The maximal thickness can be reduced by slightly decreasing the width p. The reason is explained as follows: the proposed dielectric-lens UC can be regarded as an isotropic and homogenous dielectric transmission line characterized by a relative effective permittivity of $\varepsilon_{\text{reff}}$. When the value of $\varepsilon_{\text{reff}}$ is approaching to 1, the bandpass frequency response of the proposed hybrid-lens is much more similar to the counterpart of the original bandpass SIW filter. Considering an extreme case that $\varepsilon_{\text{reff}}$ =1, the APDSP-based dielectric lens is physically equivalent to the air. In this case, the bandpass frequency response of the proposed hybrid-lens is absolutely identical to that of the original bandpass SIW filter. On the other hand, a small ε_{reff} means a small β; then the relative phase shift of the APDSP-based dielectric lens is decreased according to $\theta=\beta*t$, where β is the phase constant of the equivalent transmission line, and t is the length of the transmission line. Therefore, a trade-off between the bandpass frequency response variations of the proposed hybrid-lens and thickness of the dielectric lens should be made.

III. Gain Filtering Transmitarray Antenna

In this section, the proposed hybrid-lens UCs are fully utilized to construct the proposed gain filtering TA antenna with full-wave analyses. It is noted that a TA antenna usually includes a TA board and a feed source. Fig. 3 (a) shows the mechanism of the proposed TA antenna that is composed of a 22 × 22 elements array. Usually, a smaller *F/D* (focal to diameter ratio) can reduce the profile and decrease the spillover loss but a bigger amplitude taper loss and quantization phase errors would be introduced [14], where *F* is the distance between the phase center of the feed source and the center of the TA board, and *D* is the diameter of the TA board as shown in Fig. 8 (a). The value of *F/D* is closely related to the aperture efficiency of the entire TA antenna. The feed used here is a Potter horn antenna operating at a millimeter-wave band whose radiation patterns in E- and H-plane are almost identical for a gain edge taper of about -10 dB. Since the Potter horn antenna with $\cos^q \theta$ function pattern radiation patterns (q=6.5) is employed in this case, F/D = 0.82 is therefore chosen to provide a proper aperture illumination with an edge taper of about -10 dB. The corresponding calculated spillover and illumination efficiencies [15] are 70.95 % and 87.20 %, respectively.

Based on the schematic diagram of Fig. 3 (a), the phase distributions on every UC of the TA board at 35 GHz are calculated and plotted as shown in Fig. 3 (b). Every square block represents a UC. Once the desired phase compensation at every UC is decided, the thickness t is easily obtained according to Fig. 2 (a). The final structure model of the proposed gain filtering TA antenna is established as shown in Fig 3 (c). Then, its reflection coefficient and radiation patterns are simulated.
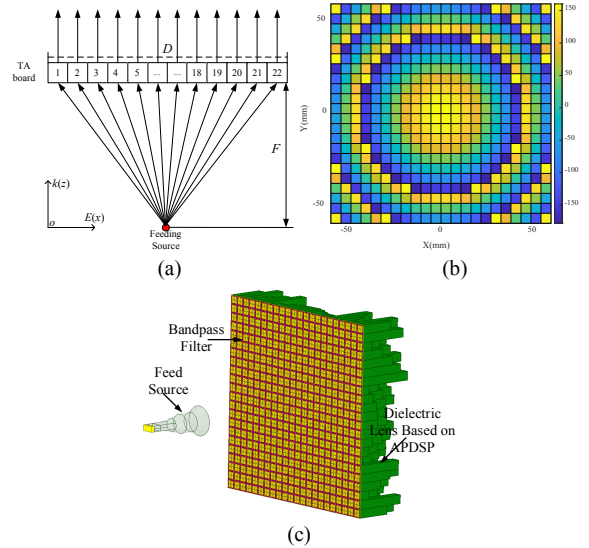

(a)   (b)

(c)

Fig. 3. (a). Phase correction mechanism for the center-fed transmitarray antenna. The red point is the phase center of the feed source (usually a horn antenna is adopted). (b). The desired phase compensations on the aperture of the proposed TA at 35 GHz. (c). The final TA model established with software.

IV. Fabrication, Measurement, and Discussion

In order to validate the effectiveness of the proposed hybrid-lens UCs, a TA antenna expected to achieve gain filtering performance at millimeter-wave band described in section Ⅲ is fabricated, measured and discussed.

A. Fabrication and reflection coefficient measurement

The SIW bandpass filter with 22 × 22 elements is fabricated by using a standard printing circuit board (PCB) technology, and the APDSP-based dielectric lens also with 22 × 22 elements is manufactured with 3-D printed technology as shown in Fig. 4 (a) and (b), respectively. The eight cylindrical air holes uniformly located at the four edges of the SIW cavity bandpass filter and APDSP-based dielectric lens are used to connect and fix them seamlessly by screws. The feed source is placed at the prescribed focus location.

(a)   (b)
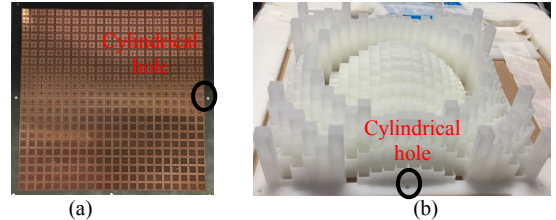
Fig. 4. Prototypes of the proposed high-gain and filtering transmitarray antenna components. (a). SIW cavity bandpass filter. (b). APDSP-based dielectric lens.
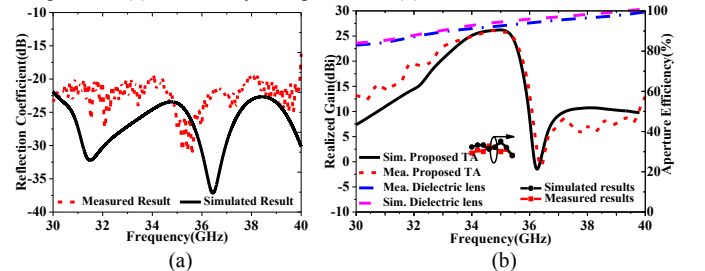

(a)   (b)

Fig.5. The comparisons of simulated and measured results. (a). The reflection coefficients of the proposed TA antenna. (b). The measured and simulated realized gains and aperture efficiency of the proposed TA antenna and dielectric lens at broadside over 30 to 40 GHz.

The reflection coefficient of the proposed TA antenna is measured with Agilent vector network analyzer (N5244A) as shown in Fig.5 (a), where the simulated reflection coefficient is also plotted for comparison. From 30 to 40 GHz, the reflection coefficients are better than -15 dB. It should be noted that the reflection coefficient response of the proposed TA antenna is not similar to the counterparts of the planar filtering antennas [17]-[20] which usually shows a high selectivity. In other words, the gain filtering property of the proposed TA antenna cannot be judged from the response of the reflection coefficient. For TA or RA antenna, the reflection coefficient is highly dependent on the feed source itself. The TA and RA boards mainly contribute to the radiation performance of the TA or RA antenna. Therefore, the gain filtering performance of the proposed TA antenna should be evaluated by observing its radiation patterns and gain response.

B. Radiation patterns and realized gain measurements

The realized gains of the proposed TA antenna at broadside from 30 to 40 GHz are measured, compared, and discussed. For comparison, the realized gains of the APDSP- based dielectric lens are also measured to highlight the gain filtering performance of the proposed TA antenna. Fig. 6 shows the experimental setup and measurement environment. The commercial pyramid absorbers are used to eliminate the electromagnetic interferences caused by the surroundings. The fixtures are utilized to fix the TA board and control the distance between the feed source with TA board. The rotary is controlled by an electrical motor to rotate 360 deg in the horizontal plane. According to Fig. 5 (b), it is observed that the measured realized gains of the proposed TA antenna indeed owns a bandpass response with frequencies, and there also exists a sharp dip in the upper band. The realized gains of the APDSP-based dielectric lens are also measured. A linear proportional relation between realized gains and frequencies is observed. The fabrication and measurement tolerances are attributed to the discrepancies between the measured and simulated results.
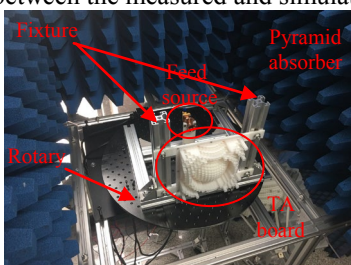

Fig. 6. Experiment setup and measurement environment.

According to Fig. 5 (b), the gain variation is less than 0.5 dB within the passband. Furthermore, the measured realized gain reaches 25.5 dBi at 35 GHz. The aperture efficiencies of the proposed TA are also calculated and plotted as shown in Fig. 5 (b), where around 30 % aperture efficiency is obtained over the entire passband. The aperture efficiency can be further improved by using a lower loss tangent dielectric material for the dielectric lens manufacture. If a higher gain filtering selectivity is needed, one can just modify the structure of the SIW bandpass filter to introduce more transmission zeros in lower or upper-frequency bands to obtain a higher selectivity.

Then, the normalized radiation patterns of the proposed TA antenna are measured at 34.5, 35, and 35.5 GHz as shown in

Fig. 7, where the simulated results are also plotted for comparison. Great agreements between the simulated and measured results are observed. The proposed TA antenna shows a pencil-beam pattern, and the main beams are highly consistent for the simulated and measured results. The measured results also reveal that the proposed TA antenna has the side lobe levels better than -20 dB in E- and H-plane, respectively, and the measured normalized cross-polarizations of the proposed TA antenna are well below -35 dB in E- and H-plane at 34.5, 35, and 35.5 GHz.
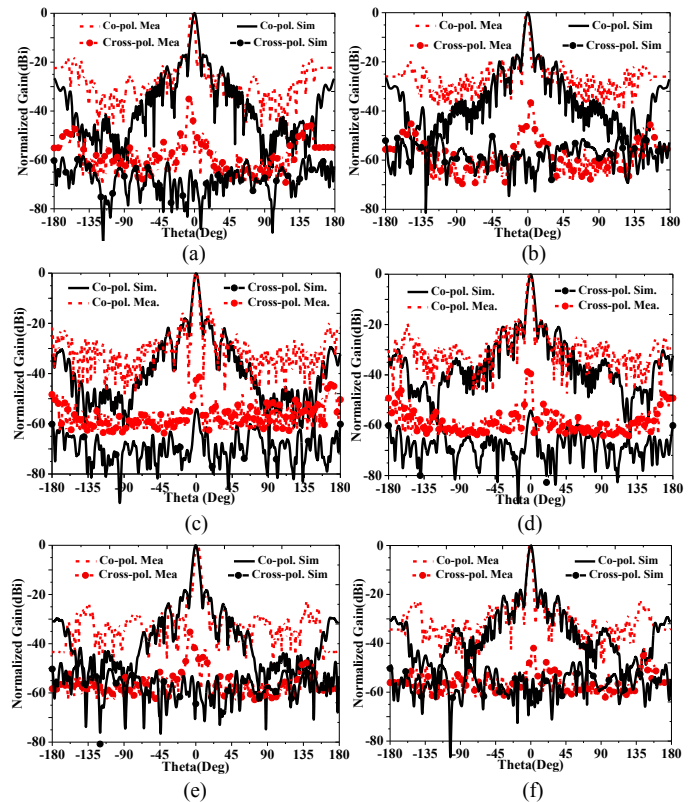

Fig. 7. The comparisons of simulated and measured normalized radiation patterns of the proposed TA antenna (a) E-plane at 34.5 GHz, (b) H-plane at 34.5 GHz, (c) E-plane at 35.0 GHz, (d) H-plane at 35.0 GHz, (e) E-plane at 35.5 GHz, (f) H-plane at 35.5 GHz.

V. CONCLUSION

In conclusion, a millimeter-wave high-gain and gain-filtering transmitarray antenna design using a hybrid-lens is presented. The proposed hybrid-lens UC is implemented with a SIW bandpass filter and an APDSP-based dielectric lens, where the APDSP-based dielectric lens UC is seamlessly coated on the SIW bandpass filter UC to achieve a co-design architecture. The simulated results reveal that the proposed hybrid-lens UC can not only maintain the bandpass response that the original SIW bandpass filter has, but also cover a full phase-cycle (2π), which is a good candidate for the gain filtering TA antenna design. The simulated and measured results are consistent, demonstrating that the proposed TA antenna indeed has high-gain and gain filtering performance. In addition, it should be noted that a TA or RA antenna can be designed with the proposed concept to obtain desired radiation performance or gain response.

REFERENCES

[1] A.Abdelrahman, P. Nayeri, A. Elsherbeni, and F. Yang, "Bandwidth improvement methods of transmitarray antennas," *IEEE Trans. Antennas Propag.*, vol. 63, no. 7, pp. 2946-2954, July 2015.

[2] M. Jazi, M. Chaharmir, J. Shaker, and A. Sebak, "Broadband transmitarray antenna design using polarization-insensitive frequency selective surface," *IEEE Trans. Antennas Propag.*, vol. 64, no. 1, pp. 99-108, Jan. 2016.

[3] K. Pham, N. Nguyen, A. Clemente, L. Palma, L. Coq, L. Dussopt, and R. Sauleau, "Design of wideband dual linearly polarized tranmistarray antennas," *IEEE Trans. Antennas Propag.*, vol. 64, no. 5, pp. 2022-2026, May. 2016.

[4] H. Nematollahi, J. Laurin, J. Page, and J. Encinar, "Design of broadband transmitarray unit cells with comparative study of different number of layers," *IEEE Trans. Antennas Propag.*, vol. 63, no. 4, pp. 1473-1481, Apr 2015.

[5] C. Huang, W. Pan, X. Ma, B. Zhao J. Cui, and X. Luo, "Using reconfigurable transmitarray to achieve beam-steering and polarization manipulation applications," *IEEE Trans. Antennas Propag.*, vol. 63, no. 11, pp. 4801-4810, Nov 2015.

[6] P. Padilla, A. Munoz-Acevedo, M. Sierra-Castaner, and M. Sierra-Perez, "Electronically reconfigurable transmitarray at Ku-band for microwave applications," *IEEE Trans. Antennas Propag.*, vol. 58, no. 8, pp. 2571-2579, Aug 2010.

[7] J. Lau, and S. Hum, "Reconfigurable transmitarray design approaches for beamforming applications," *IEEE Trans. Antennas Propag.*, vol. 60, no. 12, pp. 5679-5689, Dec 2012.

[8] L. Palma, A. Clemente, L. Dussopt, R. Sauleau, P. Potier, and P. Pouliguen, "Circularly-polarized reconfigurable transmitarray in Ka-band with beam scanning and polarization switching capabilities," *IEEE Trans. Antennas Propag.*, vol. 65, no. 2, pp. 529-530, Feb 2017.

[9] H. Yi, S. Qu, K. Ng, C. Chan, and X. Bai, "3-D printed millimeter-wave and terahertz lenses with fixed and frequency scanned beam," *IEEE Trans. Antennas Propag.*, vol. 64, no.2, pp. 442-449, Feb. 2016.

[10] P. Nayeri, *et al.*, "3D printed dielectric reflectarrays: low-cost high-gain antennas at sub-millimeter waves," *IEEE Trans. Antennas Propag.*, vol. 62, no.4, pp. 2000-2008, Apr. 2014.

[11] M. Al-Nuaimi. and W. Hong, "Discrete dielectric reflectarray and lens for E-band with different feed," *IEEE Antenas Wireless Propag. Lett.*, vol. 13, pp. 947-950, 2014.

[12] J. Rodriguez, H. Hristov, and W. Grote, "Fresnel zone plate and ordinary lens antennas: Comparative study at microwave and terahertz frequencies," *in Proc. 41st Eur. Microw. Conf.*, pp. 894-897, 2011.

[13] G. Luo, W. Hong, H. Tang, J. Chen, X. Yin, Z. Kuai, and K. Wu, "Filtenna consisting of horn antenna and substrate integrated waveguide cavity FSS," *IEEE Trans. Antennas Propag.*, vol. 55, no. 1, pp. 92-98, Jan. 2007.

[14] D. Pozar, S. Targonski, and H. Syrios, "Design of millimeter wave microstrip reflectarrays," *IEEE Trans. Antennas Propag.*, vol. 45, no. 2, pp. 287-296, Feb. 1997.

[15] A. Yu, F. Yang, A. Z. Elsherbeni, J. Huang, and Y. Rahmat-Samii, "Aperture efficiency analysis of reflectarray antennas," *Microw. Opt, Technol. Lett.*, vol. 52, no. 3, pp. 771-779, Mar 2004.

[16] C. Ryan, *et al.*, "A wideband transmitarray using dual-resonant double square rings," *IEEE Trans. Antennas Propag.*, vol. 58, no. 5, pp. 1486-1493, May. 2010.

[17] Y. Yusuf, X. Gong, "Compact low-loss integration of high-Q 3-D filters with highly efficient antennas," *IEEE Trans. Microw. Theory Tech.*, vol. 59, no. 4, pp. 857-865, Apr 2011.

[18] C. Mao, S. Gao, Y. Wang, Z. Wang, F. Qin, B. Sanz-Izquierdo, and Q. Chu, "An integrated filtering antenna array with high selectivity and harmonics suppression," *IEEE Trans. Microw. Theory Tech.*, vol. 64, no. 6, pp. 1798-1805, June 2016.

[19] C. Lin, and S. Chung, "A filtering microstrip antenna array," *IEEE Trans. Microw. Theory Tech.*, vol. 59, no. 11, pp. 2856-2863, Nov 2016.

[20] C. Lin, and S. Chung, "A compact filtering microstrip antenna with quasi-elliptic broadside antenna gain response," *IEEE Antenas Wireless Propag. Lett.*, vol. 10, pp.381-384, 2011.