

A Metasurface Loaded Wideband High-Gain Filtering Antenna Array for CubeSat Application

Naveed Ullah, Zhou He, and Yejun He, *Senior Member, IEEE*

Abstract—This letter presents a Ka-band high-gain antenna array loaded with a three-layer metasurface (MS) superstrate filter for radiation-domain filtering and in-band gain enhancement. The reference radiator source is a single-port 8×8 patch array designed at the 29.2 GHz center frequency. A new shape three-layer bandpass MS filter with a good roll-off factor is positioned above the array with an optimized air gap. Unlike conventional filtering antennas that mainly exhibit selectivity in the input reflection coefficient, the proposed structure shows its dominant filtering effect in the realized-gain and efficiency responses, while maintaining acceptable impedance matching. The operating mechanism uses the MS's bandpass transmission response and the induced E-field on the MS superstrate by the incident wave of the reference array. This configuration simultaneously enhances in-band realized gain through constructive interference, while suppressing out-of-band radiation via the MS's frequency-selective rejection. Simulated and measured results confirm that the proposed MS-loaded filtering array preserves good in-band matching from 27.5–31 GHz, covering the Ka-band uplink, and improves the boresight gain by approximately 3.1 dBic at 29.2 GHz, while attenuating the undesired lower band (LB) gain by 21.1 dBic and the upper band (UB) by 20.4 dBic. These metrics make it suitable for Ka-band CubeSat communication systems.

Index Terms—Circularly polarized (CP), Filtering array, High-gain, Ka-band, Metasurface (MS).

I. INTRODUCTION

HIGH-gain Ka-band CP antenna arrays are attractive for CubeSat communication systems because of their compact size, large available bandwidth, and ability to support high-data-rate links. Due to the congested RF environment in satellite communication, strong in-band radiation often requires suppression of undesired out-of-band radiation to reduce adjacent-band interference and improve spectral purity [1]. Filtering mechanism in antennas can provide an elegant way to combine radiation and frequency selectivity in a single structure.

Manuscript received May 30, 2026. This work is supported in part by National Key Research and Development Program of China under Grant 2023YFE0107900, in part by the National Natural Science Foundation of China (NSFC) under Grant U2541208, in part by the Key Program of Shenzhen Natural Science Foundation under Grant JCYJ20241202124219023, and in part by the Program of Shenzhen Key Laboratory Evaluation under Grant SYSPG20241211173908022.

Naveed Ullah and Yejun He are with the State Key Laboratory of Radio Frequency Heterogeneous Integration, Sino-British Antennas and Propagation Joint Laboratory of MOST, Guangdong Engineering Research Center of Base Station Antennas and Propagation, Shenzhen Key Laboratory of Antennas and Propagation, College of Electronics and Information Engineering, Shenzhen University, Shenzhen 518060, China. (e-mail: naveedullah@szu.edu.cn; heyejun@126.com)

Zhou He is with the Department of Mechanical Engineering, University of Maryland, College Park, MD 20742, USA (e-mail: zhe12@umd.edu).

Conventionally, filters and antennas in RF front ends are designed as separate modules [2], [3]. This approach not only increases the overall system complexity, but can also degrade in-band performance due to mismatched interconnections and additional insertion loss. To overcome these limitations, researchers have focused on co-designs and self-filtering [4], [5], [6], [7]. Although these methods reduce or eliminate the need for discrete bandpass filters and external filtering circuits, while maintaining sharp roll-off characteristics on both sides of the passband. However, the use of lumped elements and multiple vias makes these single-element designs complex and challenging to implement in arrays.

MS filters are particularly attractive because they can tailor both the transmission magnitude and phase observed at the radiating aperture [8], [9]. A properly designed bandpass MS filter can support constructive broadside radiation in the desired band, while weakening radiation outside the operating band. This mechanism is especially useful in large arrays, where the superstrate can modify the overall aperture field distribution in a single module. Based on this, different metasurface approaches have been used for filtering in antenna arrays and gain enhancement [10], [11], [12], [13], [14]. Furthermore, cavity-based advanced filtering antenna concepts have been implemented at multiple frequency bands [15], [16], [17], [18]. Although, these periodic structures are often utilized to construct partially reflective surfaces (PRS) [19], [20]. Nevertheless, the majority of such surfaces merely provide partial reflection/transmission of incident waves without offering complete frequency-selective filtering functionality. Moreover, certain metasurfaces have been employed in high-frequency antennas, which only achieve gain enhancement at a single resonant frequency, thereby resulting in inherently narrow bandwidths. Despite these advances, most existing filtering antenna designs are limited to single-element configurations, thick horn-fed metasurface structures, and small arrays, making it challenging to extend such designs to high-gain arrays. Additionally, achieving a filtering response in the large array's spatial parameters, such as gain and efficiency, is quite challenging.

In this work, we proposed and investigated a CP high-gain 8×8 Ka-band patch array loaded with a low insertion loss and wideband three-layer MS filter. The design operates at the center frequency of 29.2 GHz. The cavity between the array and the MS is optimized to ensure spatial filtering, gain improvement, and impedance matching. A distinctive feature of this design is that the primary filtering properties manifest in the gain and efficiency vs frequency responses. Consequently, the proposed antenna is characterized as a high-

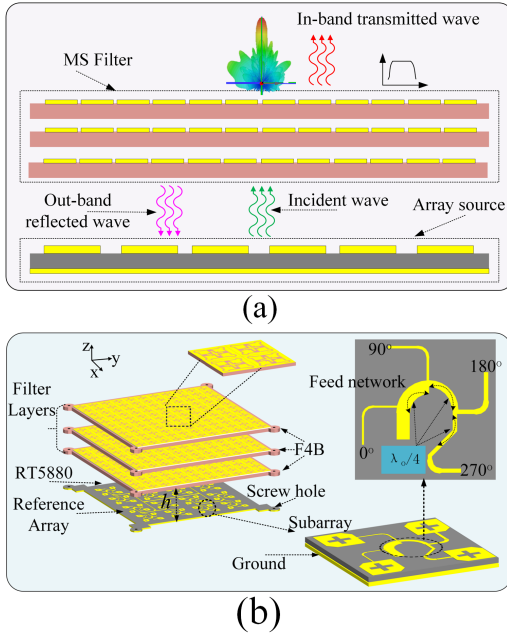


Fig. 1. Working mechanism of the design and (b) Perspective view of the proposed filtering array.

gain spatial filtering array for low Earth orbit (LEO) CubeSat communication applications.

II. DESIGN PROCESS AND ANALYSIS OF THE PROPOSED FILTERING ARRAY

A. Working Principle

The operating principle and proposed design configuration of the filtering antenna array are depicted in Fig. 1(a, b), respectively. The whole antenna mainly consists of three MS layers on the top and a single-layer CP feed antenna array located below the bandpass MS filter. The cavity spacing between the array and the MS filter is a key parameter because it determines the phase delay accumulated in the air gap to maintain the radiation pattern.

The polarization-insensitive MS is designed to function as a spatial filter within the proposed frequency band. The incident wave from the antenna array passes through the MS in its passband and radiates into the free space, while out-of-band waves are reflected.

B. Reference Array Source

The reference source is a single-fed 8×8 microstrip patch array operating in the 27.5–31 GHz range, which covers the Ka-band uplink. The array is designed on a 0.508 mm-thick dielectric Rogers RT5880 substrate with relative permittivity $\epsilon_r = 2.2$ and loss tangent $\tan \delta = 0.0009$. Each radiating element is a 2.97×2.97 mm² corner-truncated square patch with a + shaped slot, tuned to 29.2 GHz. The spacing between the elements is chosen as $0.62\lambda_0$, Where λ_0 denotes the free-space wavelength at 29.2 GHz. The 2×2 subarray consists of sequentially rotated patch elements excited with equal amplitude fed with a progressive phase shift of (0°, 90°, 180°, and 270°). The feed network is implemented using a

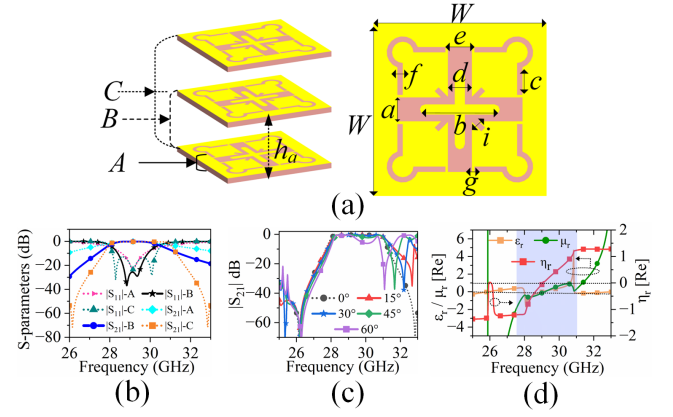


Fig. 2. (a) Meta-element with parameters (in mm): $a = 0.93$, $b = 3.14$, $c = 1.03$, $d = 0.38$, $e = 0.93$, $f = 0.21$, $g = 0.15$, $i = 0.18$ (b) Simulated S-parameters (c) Scan angle performance of the meta-atom in terms of transmission coefficient, and (d) Extracted constitutive parameters of the meta-atom.

combination of sequential rotation, as presented in the 2×2 subarray [21], and a corporate power divider to ensure 90° phase-delay excitation across the elements, achieving both wideband circular polarization and impedance matching. The simulated array yielded a wideband, a peak gain of 22.2 dBic, and an axial ratio less than 3 dB in the proposed band as discussed in section (II-D).

The feeding source array was first optimized to achieve the required results over the targeted band. After this baseline design was established, the MS superstrate filter was introduced above the radiating aperture to study its effect on the matching and radiation responses.

C. Design of Meta-atom

The simulated structure of the proposed MS unit cell, as shown in Fig. 2(a), has evolved from structure A to C in three steps for wideband operation to cover the targeted band. It consists of three 0.5 mm-thick F4B substrates with relative permittivity $\epsilon_r = 2.2$ and loss tangent $\tan \delta = 0.002$. Each substrate features with an identical conductive layer on one side and successive substrates are spaced by $h_a = \lambda_0/4$ air gaps. The metallic layers consist of a square patch loaded with multiple integrated slots and a cross-shaped conductive structure in the center. The dimensions of the suggested square unit cell are $W \times W = 6 \times 6$ mm², and other optimized parameters as shown in Fig. 2(a).

The evolution of the unit cell design to expand the operating bandwidth is illustrated by the S-parameters in Fig. 2(b). In Design-A, the $|S_{11}|$ and $|S_{21}|$ are well achieved at 29.2 GHz. However, the operating bandwidth is low, and the meta-atom functions only as a partially transmissive element. Utilizing Design-B, the air cavity distance is optimized to achieve wider bandwidth, minimized in-band reflection, and low transmission across the stopbands. However, the frequencies are still uncovered. Design-C is proposed to obtain complete bandpass filtering properties with enhanced selectivity. The final filtering MS unit cell reflection loss is < -10 dB, and the insertion loss is < 0.5 dB. Deep suppression at lower and upper frequencies

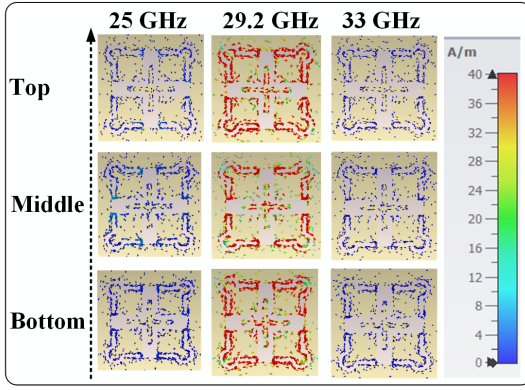


Fig. 3. Surface current on each layer of the meta-atom at 25, 29.2, and 33 GHz, respectively.

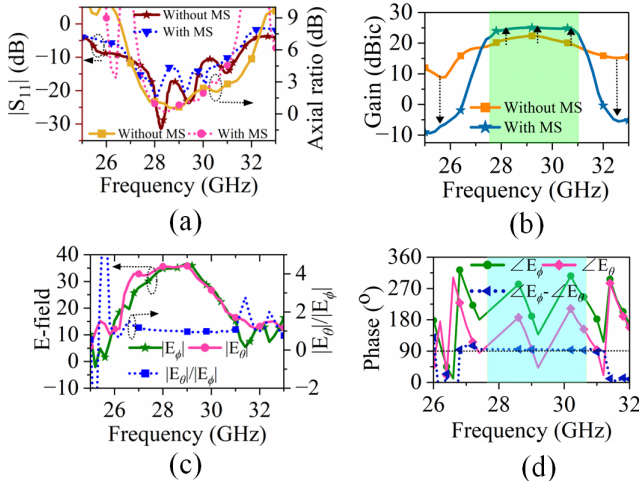


Fig. 4. (a, b) S-parameters, axial ratio, and realized gain with/without metasurface, respectively (c, d) Magnitude ratio and relative phase of the E-field orthogonal components.

is approximately -72 dB and symmetrical, along with two transmission zeros.

The roll-off factor at LB and UB is 6 dB/ 0.25 GHz, calculated according to the 3 dB and 20 dB points criteria in [22]. Moreover, the unit cell was simulated for incident angles of 0° , 15° , 30° , 45° , and 60° to verify its angular stability, as displayed in Fig. 2(c). For incident angles of 15° and 30° , the transmission magnitude ($|S_{21}|$) remained well preserved across the operating band, with noticeable changes near the UB edge. A slight increase in insertion loss was observed at 45° , whereas a significant increase occurred at 60° , indicating reduced angular stability at larger scan angles. Moreover, the maximum surface current at the center frequency and the minimum currents at the out-of-band frequencies are shown in Fig. 3, validating the effective filtering characteristics of the proposed MS.

Finally, the extracted constitutive parameters (ϵ_r , μ_r , and n_r) in Fig. 2(d) confirm the metamaterial properties of the suggested MS. The relative permittivity exhibits dispersive electric resonance with negative region near the resonance frequency, while effective permeability remains relative stable in the operating band, indicating the filtering response is mainly governed by E-field. Further, the refractive index(RI)

undergoes a smooth transition from negative to positive values, providing enhanced phase manipulation.

D. Analysis of the final design

After the reference array and the MS bandpass filter were individually designed and simulated, they were integrated to evaluate the effect of the MS on the overall antenna performance. The optimized cavity height ($h=6.7$ mm) provided a favourable compromise between matching and radiation performance. Comparative analyses were conducted for configurations with and without the MS, considering key simulated plots, including $|S_{11}|$, axial ratio (AR), and realized gain, as given in Fig. 4(a, b), respectively. The MS filter maintains satisfactory impedance matching within the operating band and axial ratio bandwidth from 27.5 to 30.3 GHz. Particularly, the in-band gain is improved by 3.1 dBic from 22.2 dBic to 25.3 dBic with the MS. Furthermore, Incorporating the wideband bandpass MS filter substantially suppresses the out-of-band gain, achieving maximum suppressions of 21.1 dBic at 25 GHz in the LB and 20.4 dBic at 33 GHz in the UB.

Similarly, the circular polarization was verified from the simulated data by calculating the magnitude ratio of the electric field components $|E_\theta|/|E_\phi| \approx 1$ and their phase difference $\angle E_\phi - \angle E_\theta \approx +90^\circ$, as shown in Fig. 4(c, d). Based on the above criteria, the two electric field components are orthogonal, and the sense of circular polarization is determined to be left-hand (LHCP).

III. EXPERIMENTAL RESULTS AND DISCUSSIONS

The fabricated design perspective and back views are shown in Fig. 5(a, b), respectively. The complete dimensions of the prototype are $7.2\lambda_0 \times 7.2\lambda_0 \times 1.3\lambda_0$. Further to verify the matching of the simulated design, the Ka-band antenna prototype was tested with the help of Vector Network Analyzer(VNA), as shown in Fig. 6(a). Fig. 6(b) presents the simulated and measured S-parameters, showing a good agreement. The measured impedance bandwidth for $|S_{11}| < -10$ dB reaches 13.4% , covering the range of 27.5 – 31 GHz.

The radiation performance of the filtering array is measured in the anechoic chamber, as displayed in Fig. 7(a). The simulated and measured axial ratio, as depicted in the Fig. 7(b), is <3 dB and closely follows each other. Fig. 7(c) compares the simulated and measured realized gains at boresight. Overall, the out-of-band gain is ≤ -5 dBic in both the stopbands. The measured gain is stable across the operating band and filtering characteristics are clearly observed in the gain plot. At centre frequency the maximum radiation efficiency is 89.3% , as presented in Fig. 7(d). Overall, the simulated and measured efficiencies of the proposed antenna are above 85% in the passband and below 5% in the stopbands (25 – 27.5 & 31 – 33 GHz). The gain and efficiency results further illustrate that the suggested antenna efficiently passes the radiation in the 27.5 – 31 GHz range while significantly suppressing it in the out-bands.

Fig. 8(a-d) illustrates the simulated and measured radiation patterns along the boresight in the E- and H-planes at 29.2 and 31 GHz. The results exhibit close similarity between

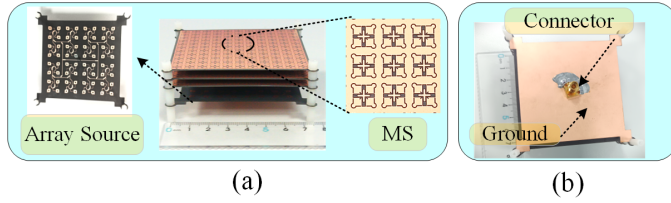


Fig. 5. (a) Different views of the fabricated design and (b) Back side of the proposed filtering array.

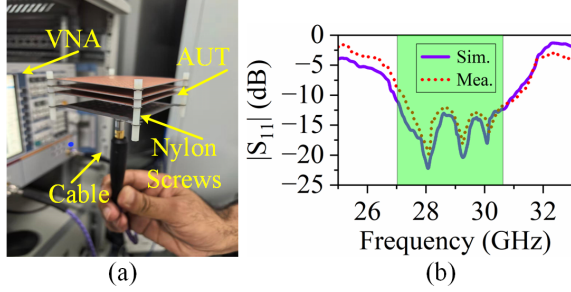


Fig. 6. (a) Prototype measurement setup and (b) Simulated and measured $|S_{11}|$.

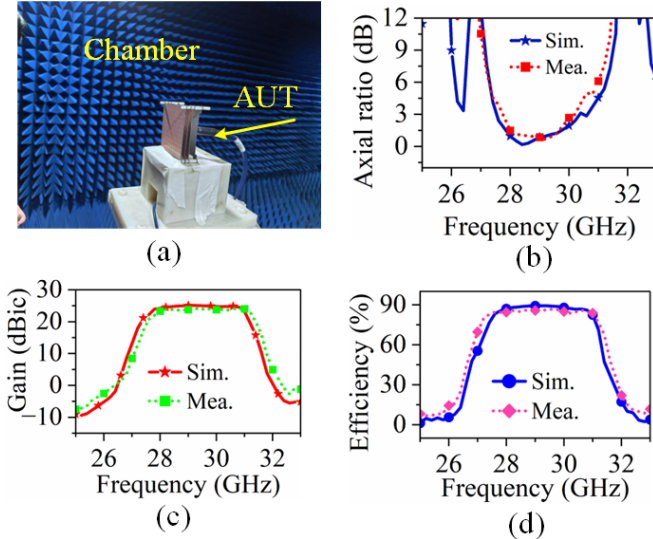


Fig. 7. (a) Anechoic chamber and antenna under test setup. Simulated and measured plots: (b-d) Axial ratio, realized gain, and efficiency(%), respectively.

simulation and measurement. The patterns are symmetrical in both planes, and the half-power beamwidths are $\sim 7.7^\circ$ and $\sim 8.3^\circ$, respectively. Moreover, the magnitude of the simulated and measured cross-polarization level is smaller than -17.6 dB and significantly lower than the magnitude co-polarization. Similarly, the side-lobe levels at the proposed frequencies are below -10 dB in both planes. The slight discrepancies in the measured results are caused by manufacturing and assembly misalignments. However, the overall results of the final filtering antenna array remain within the acceptable range.

IV. COMPARISON

Table I presents a comparative summary of the proposed MS-loaded array with other cavity-based and MS-filtering antenna designs reported in the literature. The existing designs

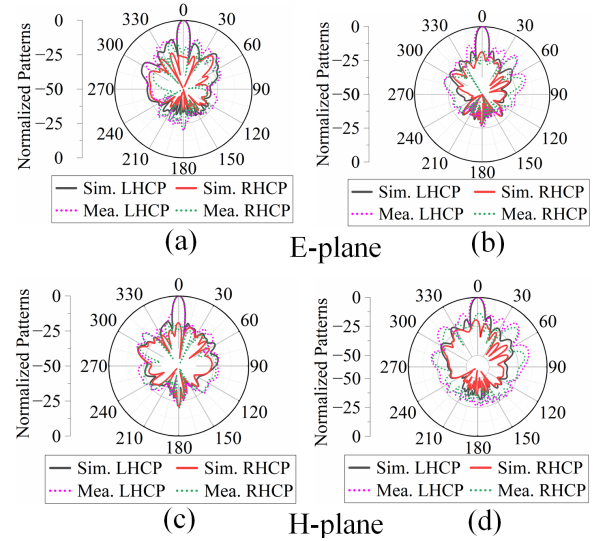


Fig. 8. Simulated and measured radiation patterns: (a, b) E-plane at 29.2 and 31 GHz and (c, d) H-plane at 29.2 and 31 GHz.

TABLE I
COMPARISON OF THE PROPOSED WORK WITH OTHER FILTERING DESIGNS.

Ref.	Freq. (GHz)	Design configuration	Complex filtering	Max. gain suppression level (dBic)	Polarization	Peak gain (dBic)	Efficiency (%)
[15]	10	Filtering cavity resonator + superstrate grid-patch	Yes	9	LP	13.7	NA
[16]	60.5	Patch + MS	No	15.2	LP	17.7	66
[17]	3	Filtering source + PRS	No	14	LP	9.5	NA
[18]	24–26.3	SIW array + FSS	Yes	9	LP	16	NA
[19]	22–30.5	Low-pass source + High-pass MS	Yes	14	LP	19.5	60
This Work	27.5–31	Array source + MS Filter	No	21.1	CP	25.3	89.3

are linearly polarized, complex, narrow-band (except [19]), and limited to single-element antennas or small arrays, also offering lower gain and radiation efficiency. In contrast, the proposed wideband 8×8 antenna array and MS configuration offer high-gain, circular polarization, good filtering properties, a simpler structure, and a high in-band radiation efficiency. With these metrics, the proposed design effectively reduces the need for additional discrete bandpass filters in the RF front end and can be efficiently used in a high-frequency CubeSat communication system.

V. CONCLUSION

A Ka-band 8×8 patch array loaded with a three-layer MS superstrate filter has been presented for radiation-domain filtering and in-band gain improvement. The proposed antenna preserves good in-band impedance matching while exhibiting a clear band-selective realized-gain and efficiency response. The fabricated prototype was measured to verify the simulated results. The relative 3 dB gain bandwidth of the proposed filtering antenna array is 11.9%, and the 3 dB AR bandwidth is 10.9%, respectively. Further, the out-band gain is significantly reduced, while the in-band gain is enhanced. Similarly, the radiation efficiency over 85% is well maintained in the band, conversely dropped to $< 5\%$ in the lower and upper stopbands, respectively.

With the advantages such as low-cost, ease of fabrication, wideband, high-gain, CP, and spatial filtering, the proposed design is a promising candidate for Ka-band CubeSat communication systems.

REFERENCES

- [1] R. S. Hao, Y. J. Cheng and Y. F. Wu, "Shared-Aperture Variable Inclination Continuous Transverse Stub Antenna Working at K- and Ka-Bands for Mobile Satellite Communication," *IEEE Transactions on Antennas and Propagation*, vol. 68, no. 9, pp. 6656-6666, Sept. 2020.
- [2] J. Deng, S. Hou, L. Zhao and L. Guo, "Wideband-to-Narrowband Tunable Monopole Antenna With Integrated Bandpass Filters for UWB/WLAN Applications," *IEEE Antennas and Wireless Propagation Letters*, vol. 16, pp. 2734-2737, 2017.
- [3] M.C.Tang, T.Shi and R. W. Ziolkowski, "Planar Ultrawideband Antennas With Improved Realized Gain Performance," *IEEE Transactions on Antennas and Propagation*, vol. 64, no. 1, pp. 61-69, Jan. 2016.
- [4] W. Hong, Z. -J. Guo and Z. -C. Hao, "Seamless Integration Technology for Filtenna Toward 5G/6G Wireless Communications," *IEEE Open Journal of Antennas and Propagation*, vol. 5, no. 1, pp. 18-36, Feb. 2024.
- [5] R. Hou, J. Ren, Y. -T. Liu, Y. -M. Cai, J. Wang and Y. Yin, "Broadband Magnetolectric Dipole Filtering Antenna for 5G Application," *IEEE Antennas and Wireless Propagation Letters*, vol. 22, no. 3, pp. 497-501, March 2023.
- [6] B. -J. Chen and X. -S. Yang, "Compact Dual-Polarized Filtering Antenna Based on Differential Feeding and Double-Layer Metasurface," *IEEE Transactions on Antennas and Propagation*, vol. 71, no. 1, pp. 1065-1070, Jan. 2023.
- [7] A. O. Nwajana, S. N. Arinze, and S. H. Ebeunuwa, "Filtering Antenna Design and Implementation Techniques: Applications, Recent Developments, Challenges, and Future Opportunities," *Journal of Engineering*, vol. 2025, 8948687, 20 pages, 2025.
- [8] R. Lu et al., "SIW Cavity-Fed Filtennas for 5G Millimeter-Wave Applications," *IEEE Trans. Antennas Propag.*, vol. 69, no. 9, pp. 5269-5277, Sep. 2021.
- [9] G. Cheng, B. Huang, Z. Huang, and L. Yang, "A High-Gain Circularly Polarized Filtering Stacked Patch Antenna," *IEEE Antennas Wirel. Propag. Lett.*, vol. 22, no. 5, pp. 995-999, May 2023.
- [10] J. Guo, Y. Chen, D. Yang, B. Ma, S. Liu, and J. Pan, "Design of a Circuit-Free Filtering Metasurface Antenna Using Characteristic Mode Analysis," *IEEE Trans. Antennas Propag.*, vol. 70, no. 12, pp. 12322-12327, Dec. 2022.
- [11] X. Zhang et al., "A Metasurface-Based Dual-Polarized Filtering Antenna with High Isolation and Wide Out-of-Band Suppression," *IEEE Antennas Wirel. Propag. Lett.*, Mar. 2026.
- [12] R. Liu et al., "Additively Manufactured Filtering Metasurface With Excellent Out-of-Band Suppression," *IEEE Trans. Microw. Theory Tech.*, 2025.
- [13] W. Yang, S. Chen, Q. Xue, W. Che, G. Shen, and W. Feng, "Novel Filtering Method Based on Metasurface Antenna and Its Application for Wideband High-Gain Filtering Antenna With Low Profile," *IEEE Trans. Antennas Propag.*, vol. 67, no. 3, pp. 1535-1544, Mar. 2019.
- [14] L. Li, Q. Ma, Z. Wu, and J. Liang, "Polarization-Reconfigurable Enhanced Ellipse-Shaped Metasurfaces Antenna with Integrated Filtering Functions," *IEEE Antennas Wirel. Propag. Lett.*, vol. 24, no. 2, pp. 424-428, 2025.
- [15] K. R. Xiang, F. C. Chen, and Q. X. Chu, "High selectivity and high gain x-band waveguide filtering antenna based on triple-mode resonator," *IEEE Trans. Antennas Propag.*, vol. 69, no. 10, pp. 6953-6958, Oct. 2021.
- [16] Q. Y. Guo, S. Nie, X. Dai, and P. Chan, "A Millimeter-Wave Filtering Fabry-Pérot Cavity Antenna," *IEEE Antennas Wirel. Propag. Lett.*, vol. 23, no. 10, pp. 3014-3017, 2024.
- [17] K.-R. Xiang and F.-C. Chen, "A Broadband Filtering Patch Antenna Using Partially Reflective Surface," *2019 International Conference on Microwave and Millimeter Wave Technology (ICMMT)*, 2019, pp. 1-3.
- [18] J. Zhang, S. Zhang, and G. F. Pedersen, "Dual-band structure reused antenna based on quasi-elliptic bandpass frequency selective surface for 5G application," *IEEE Trans. Antennas Propag.*, vol. 68, no. 11, pp. 7612-7617, Nov. 2020.
- [19] Q. -Y. Guo, J. X. Xu, W. He and H. Wong, "A High-Gain and Wideband Filtering Millimeter-Wave Fabry-Pérot Cavity Antenna Enabled by High-Pass Source and Low-Pass Surface," *IEEE Trans. Antennas Propag.*, vol. 71, no. 7, pp. 5684-5694, July 2023.
- [20] S. -Q. Zhang, S. -W. Wong, Y. He and Z. Zhang, "A Wideband Fabry-Pérot Cavity Filtering Antenna," *2024 IEEE International Workshop on Radio Frequency and Antenna Technologies (iWRF&AT)*, Shenzhen, China, 2024, pp. 283-285.
- [21] N. Ullah, S. U. Rahman, Y. Liu, and F. Wang, "A left hand circularly polarized (LHCP) wideband antenna array based on artificial magnetic conductor for Ka-band applications," *Optik (Stuttg.)*, vol. 284, Aug. 2023.
- [22] G. W. Chen et al., "High Roll-Off Frequency Selective Surface with Quasi-Elliptic Bandpass Response," *IEEE Trans. Antennas Propag.*, vol. 69, no. 9, pp. 5740-5749, Sep. 2021.