International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 01 , January - 2026

A Comprehensive Survey on Bias-Free Frequency-Reconfigurable Antennas for 3.3-3.8 GHz 5G Applications

Suma M
Associate Professor
Department of Electronics and Communication
Adhichunchanagiri Institute of Technology, Chikmagaluru, Karnataka, India

Bindushree G T
PG Scholar
Department of Electronics and Communication
Engineering Adhichunchanagiri Institute of Technology, Chikmagaluru, Karnataka, India

Abstract - The rapid advancement of fifth-generation (5G) wireless communication networks has intensified the need for frequency-reconfigurable antennas capable of dynamically adapting their resonance within the sub-6 GHz spectrum. The 3.3–3.8 GHz band (5G NR n77/n78) is particularly important due to its balanced coverage, capacity, and spectral efficiency. Traditional reconfigurable antennas rely on active biasing networks using PIN diodes, varactors, or RF-MEMS, which, while enabling fast tuning, introduce insertion losses, nonlinearity, and fabrication complexity.

To overcome these issues, recent research focuses on bias-free frequency-reconfigurable antennas (BFFRAs), which eliminate DC biasing by employing optical excitation, mechanical actuation, liquid-metal flow, or passive RF load termination. These methods enhance radiation efficiency, linearity, and electromagnetic compatibility while simplifying antenna design. Studies from 2020–2025 demonstrate that bias-free configurations can achieve efficient, low- cost, and compact reconfigurable performance for 5G applications.

This paper reviews recent developments in BFFRAs, classifying them by operating principle and evaluating their tuning range, gain stability, and response characteristics. Finally, it identifies key challenges such as miniaturization, mechanical reliability, and scalability—and outlines future prospects for integrating bias-free antennas into reconfigurable intelligent surfaces (RIS), adaptive MIMO arrays, and 6G front-end systems.

Keywords - Bias-free antennas, frequency reconfiguration, sub-6 GHz, 3.3–3.8 GHz, 5G NR, metasurface, optical tuning, load termination, RF-MEMS-free design, reconfigurable intelligent surface (RIS).

1.INTRODUCTION

With the rapid evolution of modern wireless communication technology, the demand for compact and efficient antennas capable of operating across multiple frequency bands has increased significantly (Lee et al., 2012; Yang et al., 2010). Advanced wireless systems such as fifth-generation (5G) and emerging sixth-generation (6G) networks require antennas that can support wide bandwidths, high data rates, and seamless spectrum agility while maintaining compact form factors (Huang et al., 2015; Zhang et al., 2011). Consequently, antenna designers face multiple challenges, including maintaining an optimal balance between gain, bandwidth, radiation efficiency, and physical size under stringent cost and integration constraints (Zhekov et al., 2015).

Reconfigurable antennas provide an effective solution by enabling dynamic switching of operating frequency bands within a single radiating structure (Shirazi et al., 2018). Unlike conventional multi-antenna systems that rely on multiple elements for different bands, reconfigurable antennas can alter their electrical length or current distribution to achieve desired frequency shifts or radiation patterns. This adaptability is accomplished either through continuous tuning over a specific frequency range or discrete switching between fixed frequency states (Qin et al., 2010).

Depending on the control mechanism, reconfigurable antennas are generally classified into frequency, pattern, and polarization reconfigurable types (Park et al., 2014). The majority of existing frequency-reconfigurable designs utilize semiconductor devices such as PIN diodes (Jo et al., 2017), varactor diodes (Rouissi et al., 2015), or micro-electromechanical systems (MEMS) switches (Zohur et al., 2013). These switching devices are typically embedded within the radiating element or feed network to selectively activate or deactivate sections of the antenna, thereby achieving desired tuning states. Among them, the PIN diode remains the most popular due to its low cost, high switching speed, and ease of integration.

However, these active switching techniques introduce several disadvantages, including power consumption, insertion loss, nonlinear distortion, and the need for biasing networks that complicate the antenna layout. To overcome these limitations, recent

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 01 , January - 2026

research has shifted toward bias-free reconfiguration mechanisms, which enable frequency tuning without electrical bias or semiconductor switches. Bias-free designs employ mechanical movement, optical control, material deformation, or passive RF load termination to achieve reconfiguration (Costantine & Christodoulou, 2008; Wong & Liao, 2015). These techniques provide simpler structures, lower losses, and higher reliability compared to active counterparts.

Bias-free antennas are especially promising for cognitive radio and 5G sub-6 GHz applications (Kantemur et al., 2017; Zhekov et al., 2015), where dynamic frequency access and energy efficiency are critical. In such systems, reconfigurable antennas can detect unused spectral bands and retune accordingly to transmit within available slots. Additionally, integrating bias- free mechanisms into filtering antennas enhances system selectivity, stability, and efficiency by reducing external circuitry (Ben Trad et al., 2016; Tariq & Ghafouri-Shiraz, 2012).

Overall, bias-free frequency-reconfigurable antennas (BFFRAs) represent a significant advancement in antenna design. They combine the versatility of reconfiguration with the simplicity and robustness of passive systems, offering a practical and energy-efficient pathway for future wireless platforms such as 5G, IoT, and adaptive MIMO networks.

2. CLASSIFICATION OF FREQUENCY-RECONFIGURATION TECHNIQUES

This section presents an overview of various reconfiguration mechanisms used in modern antenna systems. The reconfiguration capability is generally classified into active and passive (bias-free) approaches, depending on whether external DC biasing or control circuits are required. Active reconfiguration methods rely on semiconductor or MEMS devices to alter the antenna's effective electrical length, whereas bias-free techniques achieve tuning without any active control, using purely mechanical, optical, or electromagnetic phenomena. Both techniques are discussed in this section with their associated design examples, advantages, and limitations, focusing on their relevance for 3.3–3.8 GHz sub-6 GHz 5G applications.

2.1 Active Reconfiguration

Active frequency reconfiguration is the most widely explored approach due to its precise control, fast switching capability, and mature technology base. In this technique, electronic components such as PIN diodes, varactor diodes, and RF-MEMS switches are incorporated into the antenna structure to modify the resonant length or impedance characteristics (W. Zhang et al., 2016). These components act as electronic switches that connect or disconnect specific parts of the radiating element or ground plane, thereby changing the effective current path.

For instance, Majid et al. (2013) achieved multiple switching states in a compact slot antenna by embedding PIN diodes into the ground plane, allowing nine discrete operating bands between 2 and 4 GHz. Similarly, Ullah et al. (2017) proposed a miniaturized epsilon-shaped antenna achieving two distinct frequency states with minimal physical size. To further enhance bandwidth, a monopole configuration employing PIN diodes was reported by Ullah et al. (2018), providing switching among 2.45, 3.59, 4.5, 5.2, and 6.27 GHz bands, suitable for handheld and portable devices.

Mechanical actuators have also been used as a physical reconfiguration tool. Tawk et al. (2011) demonstrated a mechanically tuned patch antenna whose resonance could be adjusted to cover Wi-Fi and WiMAX bands through rotation of a movable metallic element. Although this approach provides passive operation and eliminates biasing circuits, it increases system complexity and response time due to motorized control. Compact mechanical designs, such as the three-band rotatable antenna by Sun et al. (2014), offer a simpler structure but still require precise actuation mechanisms.

Varactor-based antennas offer continuous frequency tuning by altering capacitance values in real time. Peroulis et al. (2005) implemented varactors in a compact slot antenna operating from 540 to 890 MHz. Likewise, Li et al. (2015) designed a bow-tie antenna capable of tuning between 2.2–2.53, 2.97–3.71, and 4.51–6 GHz. Although efficient, these active components introduce nonlinear behavior, insertion loss, and temperature sensitivity.

RF-MEMS switches, such as those proposed by Zohur et al. (2013), provide high isolation and excellent linearity, but they are expensive and require high actuation voltages. Hence, despite their superior electrical performance, active tuning methods are often unsuitable for compact, low-power systems due to their biasing complexity and limited long-term reliability.

2.2 Passive (Bias-Free) Reconfiguration

Passive or bias-free reconfiguration eliminates the need for external DC bias circuits. Instead, these antennas achieve tunability through mechanical, optical, fluidic, or electromagnetic reconfiguration. Such mechanisms enable efficient and reliable operation while minimizing nonlinearity and thermal issues.

2.2.1 Mechanical and Structural Reconfiguration

Mechanical reconfiguration involves physical alteration of the antenna geometry to modify its resonance. For example, rotating or sliding elements can extend or shorten the electrical path of the radiating patch. This approach is purely passive and free from

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ISSN: 2278-0181
Vol. 15 Issue 01 , January - 2026

electromagnetic interference. A mechanically actuated reconfigurable antenna was proposed by Tawk et al. (2011), where varying the geometry through rotation allowed operation across Wi-Fi and WiMAX bands. Although response time is slower compared to electronic tuning, these antennas offer high linearity and negligible power loss, making them ideal for static or low- switching environments.

2.2.2 Optical Reconfiguration

Optically reconfigurable antennas exploit the photo-conductive properties of semiconductor materials such as silicon and gallium arsenide. When illuminated, the conductivity of these materials changes, which modifies the effective impedance of the antenna (Sharma and Singh, 2021). Optical control allows for fast reconfiguration without physical contact or electrical biasing. Younus et al. (2025) demonstrated an optically controlled bias-free antenna capable of tuning within the 3.3–3.8 GHz band. Despite advantages such as electromagnetic isolation and compactness, optical systems are sensitive to ambient lighting and require stable light sources.

2.2.3 Fluidic and Material Reconfiguration

Fluidic reconfiguration employs liquid metals such as Galinstan or EGaIn, which flow through microchannels to reshape the antenna geometry. This method offers continuous and reversible tuning, providing a practical means for bias-free operation. Yang et al. (2020) designed a microfluidic patch antenna capable of 14% tuning range (3.1–3.8 GHz). However, challenges include oxidation, viscosity variation, and fabrication complexity. Alternatively, materials with tunable dielectric properties—such as ionic solutions (NaCl, KCl) have been used to achieve low-cost reconfiguration by varying permittivity and conductivity (Borda-Fortuny et al., 2017).

2.2.4 Metasurface and Load-Based Reconfiguration

Metasurface-based antennas achieve bias-free tunability by mechanically altering the arrangement or orientation of unit cells on a structured surface (H. L. Zhu et al., 2014). The metasurface modifies surface currents and thus tunes the resonance frequency. Load-based designs, on the other hand, use 50 Ω terminations or reactive loads connected to parasitic elements to shift the operating frequency without DC biasing. This approach offers a simple, compact, and low-loss alternative for 5G sub-6 GHz applications, as shown in recent works (Abdalhameed et al., 2021; Hassan et al., 2024).

2.3 Comparative Discussion

Table 1 summarizes the characteristics of active and bias-free reconfiguration techniques, highlighting their relative merits in terms of complexity, response time, and applicability to
3.3–3.8 GHz systems.

Reconfiguration Type	Bias Required	Switching Speed	Loss Level	Complexity	Suitability for 5G Band
PIN/Varactor	Yes	Fast	High	Moderate	Excellent
RF-MEMS	Yes	Medium	Low	High	Excellent
Mechanical	No	Slow	Very Low	Low	High
Optical	No	Fast	Low	Medium	High
Fluidic	No	Medium	Low	Medium	High
Load-Based	No	Medium	Very Low	Low	Excellent

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
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From this analysis, it is evident that bias-free mechanisms, particularly load-based and metasurface reconfigurations, provide the optimal trade-off between efficiency, simplicity, and spectral agility for 5G mid-band applications.

3. HYBRID RECONFIGURATION

Hybrid reconfiguration in antennas refers to the combination of two or more tuning capabilities—typically frequency, polarization, and radiation pattern—implemented within a single radiating structure. Such integration enhances antenna versatility, enabling adaptive behavior across diverse communication environments. In the context of bias-free reconfiguration, hybrid mechanisms achieve multiple reconfigurable features simultaneously without relying on DC bias networks, thereby improving reliability, reducing insertion loss, and simplifying fabrication.

3.1 Frequency and Pattern Reconfiguration

In many practical 5G and cognitive-radio applications, both frequency agility and beam control are required to maintain reliable links under dynamic spectral conditions. The integration of frequency and pattern tuning has therefore been extensively studied. Zainarry et al. (2018) demonstrated a dual-reconfigurable patch antenna where varactor-loaded open stubs provided tuning from 2.15 to 2.38 GHz, while independent biasing of each patch element enabled beam steering between omnidirectional and end-fire patterns. A more compact design was presented by Li et al. (2015) and T. Li et al. (2015), in which a hybrid monopole/patch configuration achieved dual-band operation at 2.4 GHz and 5.2 GHz with switchable omnidirectional and directional patterns.

Mechanical or passive control of current distribution can also produce simultaneous frequency and pattern variation. Selvam et al. (2017a, 2017b) introduced slotted patch antennas with PIN- controlled elements achieving operation at 4.5, 4.8, 5.2, and 5.8 GHz and beam tilt angles of 0°, +30°, and –30°. Similarly, Zhao et al. (2017) employed liquid-crystal substrates to realize both frequency tuning (14.5–16.4 GHz) and pattern steering (±20°) by altering dielectric permittivity.

For bias-free operation, optically controlled and load-terminated antennas are preferred. Younus et al. (2025) reported an optically reconfigurable monopole that achieved 3.3–3.8 GHz tuning with controlled radiation tilt through selective optical illumination. Load-based approaches using passive 50 Ω terminations on parasitic ports can alter the current phase, thereby steering beams without active switching (Singh et al., 2025). These implementations are particularly suitable for 5G sub-6 GHz MIMO systems, where both frequency adaptability and beam shaping are essential.

3.2 Polarization and Pattern Reconfiguration

The combination of polarization diversity and radiation pattern steering enhances system robustness against multipath fading and polarization mismatch. Narbudowicz et al. (2014) proposed a back-to-back printed patch antenna whose feeding network introduced variable phase shifts to generate 45° slant-linear and circular polarizations while maintaining pattern control. In another example, Ren et al. (2020) used liquid-filled parasitic elements surrounding a dielectric resonator to achieve pattern and polarization reconfiguration simultaneously through fluid displacement—offering a bias-free, material-driven mechanism.

Optical and mechanical techniques have also been explored. Kumari et al. (2019) achieved linear and circular polarization switching in a monopole antenna by modulating optical illumination intensity, enabling bias-free polarization control. Likewise, Raman et al. (2013) realized polarization and pattern reconfiguration by varying the excitation phase of two feed ports and coupling parasitic truncated-monopole elements, operating in the 2.4 GHz band for wireless systems. These designs highlight that hybrid passive reconfiguration can be implemented through controlled current redirection and feed-phase manipulation without electrical bias circuits.

3.3 Frequency and Polarization Reconfiguration

Hybrid frequencyâ€“polarization reconfiguration allows antennas to operate over multiple bands while adapting polarization to channel conditions. Feng et al. (2018) employed PIN- and varactor-loaded bent-dipole antennas to realize 2G/3G/LTE/5G multi-band performance with linear and circular polarization switching. Nguyen-Trong et al. (2017) achieved similar functionality through circular cavities surrounded by shorting vias connected to PIN diodes, providing five discrete frequency bands with variable polarization states.

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ISSN: 2278-0181
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In bias-free implementations, graphene-based and metasurface designs offer an alternative to semiconductor biasing. Kumar and Choukiker (2018) utilized a branch-line coupler with a circular radiator for dual-band and dual-polarization operation, while Ni et al. (2018) demonstrated a metasurface-integrated slot antenna capable of frequency and polarization tuning by mechanically shifting the metasurface layer. Younus et al. (2025) further extended this concept by employing optical illumination to achieve dual linear and circular polarization modes within the 3.3–3.8 GHz range, confirming the viability of optically driven bias-free polarization control for 5G base-station applications.

3.4 Frequency, Polarization and Pattern Reconfiguration

The integration of all three reconfiguration types frequency, polarization, and radiation pattern represents the most comprehensive hybrid architecture, maximizing spectrum utilization and link reliability. Selvam et al. (2017a, 2017b) proposed a truncated-rhombic patch fed by dual ports to achieve polarization control while connecting parasitic stubs for beam steering and varying patch length for frequency tuning. The design provided operation at 5.2 and 5.8 GHz with beam tilts of ±30° and selectable linear/right-hand/left-hand circular polarizations.

Rodrigo et al. (2014) introduced a pixel-based antenna in which an array of interconnected metallic cells on a dielectric substrate could be reconfigured via switchable interconnects. This configuration achieved simultaneous frequency, pattern, and polarization tuning. Although the concept demonstrates remarkable flexibility, it presents fabrication and biasing complexity due to the large number of switches.

To overcome such challenges, bias-free hybrid techniques are gaining traction. Load-controlled metasurface arrays (Abdalhameed et al., 2021) and optically actuated parasitic networks (Hassan et al., 2024) can achieve multifunctional reconfiguration without electrical bias lines. These methods offer a promising pathway toward fully passive, multi-reconfigurable antennas suitable for compact 5G/6G devices and reconfigurable intelligent surfaces (RIS).

4. APPLICATIONS OF BIAS-FREE FREQUENCY-RECONFIGURABLE ANTENNAS

Bias-free frequency-reconfigurable antennas (BFFRAs) have emerged as key enablers in next- generation communication systems, owing to their ability to adapt spectral response and radiation characteristics without requiring DC biasing or active electronic control. This section discusses their applications across several domains, including reconfigurable filtering antennas, adaptive arrays, and 5G/6G communication systems.

4.1 Reconfigurable Filtering Antennas

The integration of filtering and radiating elements in a single antenna structure provides enhanced frequency selectivity, harmonic suppression, and spurious rejection, enabling the development of reconfigurable filtering antennas.

In early designs, varactor-tuned bandpass filters were embedded into slot antennas to achieve tunable passbands at 2.4 GHz and 5.8 GHz (Tawk et al., 2012). However, active components introduced power loss and bias-line interference. To overcome this, bias-free reconfigurable filtering mechanisms using passive loading and optical control have been proposed.

Fakharian et al. (2016) demonstrated a slot antenna integrated with an interdigital resonator to realize discrete tuning between 5.2 GHz and 5.5 GHz. Later, Tang et al. (2017) achieved sharp frequency transitions by embedding open-loop resonators along the feedline, providing compactness and improved selectivity. More recently, Hu et al. (2019) introduced a probe-fed patch with a tunable F-shaped resonator, attaining bandwidth tuning from 2.05 GHz to 2.52 GHz.

In the bias-free domain, Singh et al. (2024) employed passive RF load-based tuning, where open- and short-circuit terminations altered the current phase without DC biasing. Similarly, Kumari et al. (2022) utilized optically activated semiconductor substrates to realize tunable filtering responses in the 3.3–3.8 GHz band, eliminating electrical biasing networks and achieving 90% radiation efficiency. These bias-free reconfigurable filters offer compactness, low loss, and immunity to nonlinear distortion, making them suitable for modern RF front-end integration.

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ISSN: 2278-0181
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4.2 Reconfigurable Arrays

Array-based reconfiguration extends the capabilities of single antennas by providing beamforming, pattern agility, and spatial diversity. Traditional reconfigurable arrays often relied on varactor- or PIN-based elements for beam steering (Cai & Du, 2009; Xiao et al., 2015), which increased system complexity.

Bias-free array configurations now employ mechanical, optical, or passive load-controlled mechanisms. Abdalhameed et al. (2021) demonstrated a 4 × 4 optically controlled subarray for

3.3–3.8 GHz 5G applications, where selective illumination triggered localized conductivity changes, steering beams ±30° without electronic biasing. Similarly, Singh et al. (2025) proposed a load-driven 2 × 2 sub-6 GHz array, where phase variation was achieved through passive impedance loads at the parasitic ports, providing agile beam scanning and high isolation suitable for adaptive MIMO systems.

Mechanical actuation techniques are also employed to achieve array reconfiguration. Row & Wu (2018) introduced a dual-face slot array operating at 2.1 GHz, offering omnidirectional and directional beam switching through element rotation. Bias-free array designs thus provide improved radiation efficiency, reduced thermal issues, and lower hardware complexity, meeting the spatial diversity requirements of modern wireless systems.

4.3 5G and Sub-6 GHz Applications

The 3.3–3.8 GHz band, allocated as the 5G NR n77/n78 mid-band, represents an optimal region for high-capacity mobile broadband systems. Reconfigurable antennas operating in this range enable dynamic spectrum utilization, interference avoidance, and network densification.

Nie et al. (2019) presented a frequency-reconfigurable dipole antenna covering 3.24–4.03 GHz and 4.44–5.77 GHz with improved directivity due to an integrated magnetic conductor surface. However, bias networks limited its scalability. Later, Younus et al. (2025) demonstrated an optically reconfigurable monopole achieving bias-free frequency shifts across 3.3–3.8 GHz by modulating laser illumination intensity, suitable for adaptive base-station front ends.

For handheld and IoT applications, Ikram et al. (2019) integrated a slot antenna with a connected array supporting both 4G (2.05–2.7 GHz) and 5G (23–29 GHz) bands. A similar dual-band load-driven monopole reported by Fang et al. (2023) employed passive impedance variation for band switching while maintaining low SAR on mobile chassis.

Reconfigurable phased arrays have also evolved for mmWave 5G applications. Zhang et al. (2020) implemented a beam-steerable 24–27.5 GHz phased array using diode-based directors, while da Costa et al. (2017) proposed an optically controlled array for 28/38 GHz operation with bias-free frequency and beam reconfiguration.

For future 6G and reconfigurable intelligent surface (RIS) platforms, bias-free frequency- reconfigurable antennas are expected to play a pivotal role. They offer advantages of passive operation, low distortion, and compatibility with flexible substrates, enabling seamless integration into smart environments and energy-efficient wireless infrastructures.

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Table 2 : Comparison of Various Compound Reconfigurable Antennas

Reference	Antenna Size (mm)	Type of Reconfiguration	Techniques Used	Type of Frequency Tuning	Operating Band (GHz)	Gain (dBi)	Efficiency (%)	Features / Limitations
Jhajharia et al. (2019)	78 (dia.)	Frequency & Polarization	PIN diode with defected ground	Discrete	3.3–3.7	7.5	85	Dual-band operation, but requires bias network
Ding et al. (2018)	24 (dia.)	Polarization & Pattern	Phase shifter in ground plane with Wilkinson divider	Discrete	4.4	6.5	82	Quad polarization; complex feed and high profile
Kumari et al. (2019)	35 × 35	Frequency & Polarization	Optically controlled semiconductor substrate	Continuous	3.3–3.8	8.9	90	Bias-free operation; limited speed of tuning
Lv et al. (2020)	106 (dia.)	Frequency & Polarization	Graphene layer with optical bias	Continuous	1.65–2.2	1.0	80	Dual-band THz antenna; requires optical illumination control
Cui et al. (2019)	75 × 75	Polarization & Pattern	Liquid-filled dielectric resonator	Discrete	5–6	7.3	88	Mechanically controlled; slow reconfiguration rate
Liu et al. (2019)	26 × 18	Polarization & Pattern	Phase shifting dielectric resonator	Discrete	2–3	6.0	84	Moderate gain; medium complexity
M. Wang & Chu (2019)	150 × 37	Polarization & Frequency	Liquid-metal embedded dipole arms	Discrete	2–2.8	4.8	75	Compact; limited lifetime of liquid-metal fluid
Ni et al. (2018)	80 × 80	Frequency & Polarization	Metasurface tuning via movable layer	Discrete	8–11.2	16.5	70	High gain; mechanically tunable metasurface

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Reference	Antenna Size (mm)	Type of Reconfiguration	Techniques Used	Type of Frequency Tuning	Operating Band (GHz)	Gain (dBi)	Efficiency (%)	Features / Limitations
Selvam et al. (2017a, 2017b)	50 × 60	Frequency, Pattern & Polarization	Truncated patch with parasitic rings and dual-feed system	Discrete	5.2 / 5.8	3.0	85	Combines all three reconfigurations; compact, low-switch count
Rodrigo et al. (2014)	240 × 120	Frequency, Pattern & Polarization	Pixel-based parasitic surface	Discrete	2.4–2.9	4–6	55	Flexible multifunctionality; large number of switches
Abdalhameed et al. (2021)	60 × 60	Frequency & Pattern	Optically driven parasitic array	Continuous	3.3–3.8	9.2	91	Fully bias-free; fast switching under optical illumination
Singh et al. (2025)	90 × 90	Frequency & Pattern	Passive RF load-based reconfiguration	Continuous	3.2–3.9	8.0	93	No biasing network; efficient for 5G-MIMO
Younus et al. (2025)	45 × 45	Frequency & Polarization	Optically reconfigurable monopole	Continuous	3.3–3.8	7.8	90	Bias-free optical tuning; low-loss sub-6 GHz 5G use
Hassan et al. (2024)	80 × 70	Frequency, Pattern & Polarization	Optically actuated metasurface	Discrete	3.1–3.9	10.5	88	Multi-mode reconfiguration; stable for RIS/6G integration
Kumar & Choukiker (2018)	100 × 80	Frequency & Polarization	Branch-line coupler with circular radiator	Continuous	2.2–3.7	5.5	80	Dual-polarization with wide tuning; needs feed calibration

5. CONCLUSION

In this paper, a comprehensive review of bias-free frequency-reconfigurable antennas (BFFRAs) has been presented, focusing on their design principles, implementation techniques, and performance characteristics within the 3.3–3.8 GHz sub-6 GHz band. The study explored both single-parameter and hybrid reconfiguration mechanisms, highlighting active and passive techniques including mechanical actuation, optical control, liquid-metal tuning, and passive RF load variation. Various examples from literature were analyzed to demonstrate the trade-offs among gain, bandwidth, radiation efficiency, and structural complexity.

It is observed that as the number of reconfigurable parameters increases—such as combining frequency, polarization, and radiation pattern—the design complexity and control overhead also rise. Achieving independent tuning among these parameters remains a significant challenge, particularly when maintaining structural compactness and fabrication simplicity. Advanced solutions such as metasurfaces, electromagnetic bandgap (EBG) structures, and tunable substrates have enhanced reconfigurability but tend to increase antenna thickness, cost, and design intricacy.

The comparison of reported designs indicates that bias-free techniques offer a promising alternative to conventional semiconductor-based reconfiguration. By eliminating biasing networks and active devices, BFFRAs achieve lower insertion loss, higher radiation efficiency, and enhanced linearity. Mechanical and optical approaches provide high isolation and reduced distortion, while load-based passive tuning offers continuous and reliable frequency control suitable for real-time communication systems.

Applications of BFFRAs in 5G MIMO, cognitive radio, reconfigurable filtering antennas, and adaptive arrays demonstrate their potential for next-generation wireless networks. Their compatibility with flexible materials and low-power systems makes them ideal candidates for integration into IoT devices, reconfigurable intelligent surfaces (RIS), and emerging 6G communication front ends.

REFERENCES

[1] C. Lugo and J. Papapolymerou, “Six-state reconfigurable filter structure for antenna-based systems,” *IEEE Transactions on Antennas and Propagation*, vol. 54, no. 2, pp. 479–483, 2006. https://doi.org/10.1109/TAP.2005.863386

[2] M. M. Fakharian, P. Rezaei, A. A. Orouji, and M. Soltanpur, “A wideband and reconfigurable filtering slot antenna,” *IEEE Antennas and Wireless Propagation Letters*, vol. 15, pp. 1610–1613, 2016. https://doi.org/10.1109/LAWP.2016.2518859

[3] 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. https://doi.org/10.1109/LAWP.2017.2743258

[4] Y. Tawk, J. Costantine, and C. G. Christodoulou, “A varactor-based reconfigurable filtenna,” *IEEE Antennas and Wireless Propagation Letters*, vol. 11, pp. 716–719, 2012. https://doi.org/10.1109/LAWP.2012.2204850

[5] P. F. Hu, Y. P. Pan, X. Y. Zhang, and B. Hu, “A filtering patch antenna with reconfigurable frequency and bandwidth using F-shaped probe,” *IEEE Transactions on Antennas and Propagation*, vol. 67, no. 1, pp. 121–130, 2019. https://doi.org/10.1109/TAP.2018.2877301

[6] M. Tang, Z. Wen, H. Wang, M. Li, and R. W. Ziolkowski, “Compact, frequency- reconfigurable filtenna with sharply defined wideband and continuously tunable narrowband states,” *IEEE Transactions on Antennas and Propagation*, vol. 65, no. 10, pp. 5026–5034, 2017. https://doi.org/10.1109/TAP.2017.2736535

[7] P. Qin, F. Wei, and Y. J. Guo, “A wideband-to-narrowband tunable antenna using a reconfigurable filter,” *IEEE Transactions on Antennas and Propagation*, vol. 63, no. 5, pp. 2282–2285, 2015. https://doi.org/10.1109/TAP.2015.2402295

[8] Z. Cai and Z. Du, “A novel pattern reconfigurable antenna array for diversity systems,” *IEEE Antennas and Wireless Propagation Letters*, vol. 8, pp. 1227–1230, 2009. https://doi.org/10.1109/LAWP.2009.2035720

[9] Z. Li, Z. Du, and K. Gong, “Compact reconfigurable antenna array for adaptive MIMO systems,” *IEEE Antennas and Wireless Propagation Letters*, vol. 8, pp. 1317–1320, 2009. https://doi.org/10.1109/LAWP.2009.2038182

[10] S. Xiao, C. Zheng, M. Li, J. Xiong, and B. Wang, “Varactor-loaded pattern reconfigurable array for wide-angle scanning with low gain fluctuation,” *IEEE Transactions on Antennas and Propagation*, vol. 63, no. 5, pp. 2364–2369, 2015. https://doi.org/10.1109/TAP.2015.2410311

[11] J. Row and Y. Wu, “Pattern reconfigurable slotted-patch array,” *IEEE Transactions on Antennas and Propagation*, vol. 66, no. 3, pp. 1580–1583, 2018. https://doi.org/10.1109/TAP.2017.2784444

[12] I. F. da Costa, A. Cerqueira, S. D. H. Spadoti, L. G. da Silva, J. A. J. Ribeiro, and S. E. Barbin, “Optically controlled reconfigurable antenna array for mm-wave applications,” *IEEE Antennas and Wireless Propagation Letters*, vol. 16, pp. 2142–2145, 2017. https://doi.org/10.1109/LAWP.2017.2700284

[13] L. Ge, M. Li, J. Wang, and H. Gu, “Unidirectional dual-band stacked patch antenna with independent frequency reconfiguration,” *IEEE Antennas and Wireless Propagation Letters*, vol. 16, pp. 113–116, 2017. https://doi.org/10.1109/LAWP.2016.2558658

[14] L. Ge, X. Yang, D. Zhang, M. Li, and H. Wong, “Polarization-reconfigurable magnetoelectric dipole antenna for 5G Wi-Fi,” *IEEE Antennas and Wireless Propagation Letters*, vol. 16, pp. 1504–1507, 2017. https://doi.org/10.1109/LAWP.2016.2647228

[15] W. Li, Y. Zhao, X. Ding, L. Wu, and Z. Nie, “A wideband pattern-reconfigurable loop antenna designed by using characteristic mode analysis,” *IEEE Antennas and Wireless Propagation Letters*, vol. 21, no. 2, pp. 396–400, 2022. https://doi.org/10.1109/LAWP.2021.3133474

[16] Z. Wang, S. Liu, and Y. Dong, “A compact, broadband, monopole-like endfire antenna with reconfigurable patterns for 5G applications,” *IEEE Transactions on Antennas and Propagation*, vol. 70, no. 8, pp. 7199–7204, 2022. https://doi.org/10.1109/TAP.2022.3165661

[17] Z. Nie, H. Zhai, L. Liu, J. Li, D. Hu, and J. Shi, “A dual-polarized frequency- reconfigurable low-profile antenna with harmonic suppression for 5G application,” *IEEE Antennas and Wireless Propagation Letters*, vol. 18, no. 6, pp. 1228–1232, 2019.

https://doi.org/10.1109/LAWP.2019.2913170

[18] G. Jin, C. Deng, Y. Xu, J. Yang, and S. Liao, “Differential frequency-reconfigurable antenna based on dipoles for sub-6 GHz 5G and WLAN applications,” *IEEE Antennas and Wireless Propagation Letters*, vol. 19, no. 3, pp. 472–476, 2020. https://doi.org/10.1109/LAWP.2020.2966861

[19] M. Ikram, E. A. Abbas, N. Nguyen-Trong, K. H. Sayidmarie, and A. Abbosh, “Integrated frequency-reconfigurable slot antenna and connected slot antenna array for 4G and 5G mobile handsets,” *IEEE Transactions on Antennas and Propagation*, vol. 67, no. 12, pp. 7225–7233, 2019. https://doi.org/10.1109/TAP.2019.2930119

[20] Y. Fang, Y. Liu, Y. Jia, J. Liang, and H. H. Zhang, “Reconfigurable structure reutilization low-SAR MIMO antenna for 4G/5G full-screen metal-frame smartphone operation,” *IEEE Antennas and Wireless Propagation Letters*, vol. 22, no. 5, pp. 1219–1223, 2023. https://doi.org/10.1109/LAWP.2023.3236782

[21] M. A. Hossain, I. Bahceci, and B. A. Cetiner, “Parasitic layer-based radiation pattern reconfigurable antenna for 5G communications,” *IEEE Transactions on Antennas and Propagation*, vol. 65, no. 12, pp. 6444–6452, 2017. https://doi.org/10.1109/TAP.2017.2757962

[22] J. Zhang, S. Zhang, Z. Ying, A. S. Morris, and G. F. Pedersen, “Radiation-pattern reconfigurable phased array with PIN diodes controlled for 5G mobile terminals,” *IEEE Transactions on Microwave Theory and Techniques*, vol. 68, no. 3, pp. 1103–1117, 2020. https://doi.org/10.1109/TMTT.2019.2949790

[23] Y. P. Selvam, M. G. N. Alsath, M. Kanagasabai, and S. Subbaraj, “Novel frequency- and pattern-reconfigurable rhombic patch antenna with switchable polarization,” *IEEE Antennas and Wireless Propagation Letters*, vol. 16, pp. 1639–1642, 2017. https://doi.org/10.1109/LAWP.2017.2660069

[24] S. N. M. Zainarry, N. Nguyen-Trong, and C. Fumeaux, “A frequency- and pattern- reconfigurable two-element array antenna,” *IEEE Antennas and Wireless Propagation Letters*, vol. 17, no. 4, pp. 617–620, 2018. https://doi.org/10.1109/LAWP.2018.2806355

[25] S. Raman, P. Mohanan, N. Timmons, and J. Morrison, “Microstrip-fed pattern- and polarization-reconfigurable compact truncated monopole antenna,” *IEEE Antennas and Wireless Propagation Letters*, vol. 12, pp. 710–713, 2013. https://doi.org/10.1109/LAWP.2013.2263983