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Review

Exploring Gap Waveguide Solutions: A Review of Millimeter-Wave Beamforming Components and Antennas for Advanced Applications

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Abstract: This review delves into the crucial role of gap waveguide (GW) technology in advancing millimeter-wave (mm-wave) communication systems, specifically focusing on the exploration of beamforming components and antennas for advanced applications. With an emphasis on achieving high-data-rate and low-latency services, GW technology becomes instrumental in the development of cost-effective mm-wave solutions. The paper investigates practical applications, highlighting various components essential for beamforming antenna systems, including mm-wave antennas with diverse polarizations, power combining and dividing components like directional couplers, and beamforming feeding networks. These components collectively contribute to the comprehensive integration of a beamforming antenna system within the mm-wave frequency band. As the mobile communication landscape evolves, GW technology emerges as a key enabler for meeting the growing demands of consumers and technology in advanced applications, as detailed in this comprehensive review of GW solutions.

Keywords: antenna systems, beamforming components, gap waveguide (GW), high data-rate, low-latency applications, millimeter-wave communication, phased arrays, RF transceivers

1. Introduction

In the realm of electromagnetic engineering, the pursuit of innovative waveguide technologies has become essential, driven by the demand for more efficient communication systems and antennas across various applications. Among these advancements, gap waveguide (GW) technology stands out as a transformative development, offering novel solutions to contemporary challenges in wireless communication and antenna design. Fundamental research has illustrated the integration of GW with antennas, demonstrating their efficiency in millimeter-wave (mm-wave) scenarios. This integration builds upon foundational studies that have explored the utility of GW in diverse applications, including local metamaterial-based waveguides, soft and hard horn antennas, and the design and experimental verification of GW. These foundational investigations, pioneered by Kildal and his collaborators [1, 2, 3, 4] have laid the groundwork for understanding the principles and potential applications of GW technology.

Transitioning from foundational research to practical applications, GW technology has catalyzed advancements in antenna systems and arrays. Engineers and researchers have used GW technology to develop a wide array of antenna systems, including bandwidth-enhanced cavity-backed slot array antennas, high-gain 60-GHz corrugated slot antenna

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arrays, and mm-wave wideband slot array antennas. These advancements, as demonstrated by the works of various researchers [5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44], have significantly improved the performance and functionality of antenna systems across different frequency bands and polarization requirements.

Expanding beyond antenna systems, the integration of GW technology into passive components and circuits has yielded remarkable advancements. Researchers have designed and implemented various components with enhanced performance and manufacturing flexibility, including wideband power dividers, narrow-band microwave filters, and integrated diplexer-antenna array modules. The seamless integration of GW technology into microwave and mm-wave circuits offers improved functionality and efficiency across a wide range of applications. Building on the success of passive components, GW technology has revolutionized dividers, couplers, and beamforming sections, offering compact and efficient signal distribution and manipulation. Reconfigurable power splitters, packaged in-phase/out-of-phase printed multilayer power dividers, and ultra-wideband hybrid directional couplers are just a few examples of the innovative devices enabled by GW technology. These advancements, demonstrated by researchers in the field [45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56], have the potential to enhance the performance and versatility of beamforming and signal distribution systems in wireless communication networks. Furthermore, the synergy between GW technology and metamaterials has unlocked the development of compact and efficient devices with unprecedented properties. Wideband artificial magnetic conductors, compact artificial magnetic conductors for super wideband radar cross-section (RCS) reduction, and high-efficiency polarization-independent artificial magnetic conductors leverage the benefits of GW technology to achieve superior performance in electromagnetic wave manipulation. These advancements, showcased in the works of researchers exploring metamaterials [57, 58], hold promise for ground-breaking advancements in electromagnetic engineering and antenna design. In addition, gap waveguide (GW) technology has been deployed alongside multiple phase shifters and beamforming networks to support various applications in the mm-wave spectrum [59, 60, 61, 62, 63, 64, 65, 66, 67, 68, 69, 70, 71, 72].

The existing guiding structures, encompassing microstrip lines, rectangular waveguides, and substrate-integrated waveguides (SIW), pose significant limitations and challenges, particularly at higher frequencies [73, 74, 75, 76, 77, 78, 79, 80, 81, 82, 83, 84]. Microstrip lines exhibit notable dielectric losses and susceptibility to leakages due to line bending, alongside the emergence of surface waves and cavity mode excitation at elevated frequencies. Rectangular waveguides, esteemed for their low loss and high Q-factor, encounter heightened fabrication complexities at mm-wave frequencies, complicating the design of feeding networks, particularly with regards to achieving electrical contact between sidewalls. Similarly, SIW, serving as a printed counterpart to rectangular waveguides, still suffers from high dielectric losses and dispersion in the mm-wave spectrum, despite offering improved performance over microstrip lines. In response, gap waveguide (GW) technology emerges as a promising alternative, effectively prohibiting surface waves within a specified bandgap and mitigating leakage issues. Moreover, GW demonstrates lower losses compared to SIW and microstrip lines, a critical advantage in the mm-wave range [33, 60].

Only a few review articles have been proposed based on GW technologies [33, 85, 86, 87]. Previous review articles have discussed antenna feeding structures and other microwave components based on GW technology. The first review article, proposed in 2015 [33], primarily emphasizes the importance of GW compared to other guiding structures. Demonstrations are provided on how GW can be beneficial in terms of power handling and low loss, and it does not require any contact between the two halves, requiring only a few plastic screws for assembly. Subsequently, in 2023, additional review articles were proposed to describe the importance of these emerging guiding structures [85, 86, 87].

In this review article, we aim to cover more advanced components based on GW technologies, supporting broader perspectives for future IoT devices, as well as future radars and satellite communications. Additionally, we investigate the transformative impact of GW technology across various topics of electromagnetic engineering. Our exploration encompasses diverse applications, including antenna systems and arrays, passive components, and circuits, as well as metamaterials and novel concepts. Through this exploration, we seek to highlight the impact of GW technology on recent electromagnetic engineering, showcasing its transformative potential across diverse applications and paving the way for future innovations in wireless communication and antenna design.

2. Fundamentals of GW technology

GW Technology stands at the forefront of mm-wave communication systems, offering innovative solutions to conventional waveguide challenges. In this section, we delve into the foundational principles that underpin GW technology. We initiate with a thorough examination of the electromagnetic bandgap (EBG) unit cell and its pivotal role in the design, simulation, and interpretation of GWs. Throughout this exploration, our objective is to dissect the core principles of GWs, elucidating their distinct advantages over traditional waveguide structures. Furthermore, we scrutinize the intricacies of unit cell analysis, with a specific focus on printed gap waveguide (PGW) technology. By elucidating these fundamental concepts, we aim to furnish a comprehensive understanding of GW technology and its profound implications for modern communication systems and antenna design.

2.1 *Principles of GW*

GW technology marks a significant advancement in addressing the challenges of wireless communication at mm-wave frequencies. It introduces a novel approach utilizing two parallel plates: one serving as a perfect electric conductor (PEC), and the other as a perfect magnetic conductor (PMC) [1, 2]. By carefully controlling the separation between the PEC-PMC parallel plate configurations to be less than a quarter wavelength, GW effectively inhibits wave propagation around the guiding structure within a specific bandgap. This innovative concept enables waves to propagate inside an air gap surrounded by periodic cells, creating a high-impedance surface [3]. These periodic unit cells ensure the propagation of a quasi-transverse electromagnetic (Q-TEM) mode within the air gap. While a PMC doesn' t naturally exist, it can be realized with a periodic structure, such as a metal bed of nails or mushrooms. Figure 1 illustrates the basic operating principle of GW technology, where incorporating a ridge surrounding the PMC surface facilitates a PEC-PEC configuration, enabling wave propagation. Conversely, the PEC-PMC configuration blocks any wave propagation transverse to the ridge direction. This innovative extension of hard and soft surfaces enhances the radiation characteristics of horn antennas by integrating corrugated surfaces [4], where the implementation of EBG structures represents a critical aspect in achieving wave propagation control.

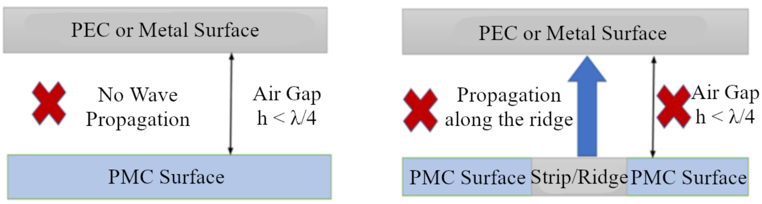

Figure 1. Theory of GW technology (ridge surrounded by PEC/PMC surfaces)

EBG structures have the capability to eliminate wave propagation in two dimensions, encompassing all polarizations and directions within a defined stopband, as determined by the unit cell dimensions. EBG surfaces are typically constructed using joints composed of metal pins arranged periodically in 2-D surfaces, commonly referred to as the 'bed of nails' [58]. Alternatively, these periodic nail arrangements can be implemented using printed circuit board (PCB) structures, where metallic pins are replaced by conducting plated vias and enclosed with a circular or square-shaped patch. Figure 2 highlights the periodic bed of nails for both metal and PCB structures. The mushroom patches depicted in Figure 2, also known as Sievenpiper mushroom cells [57], consist of square patches situated on a grounded dielectric substrate connected to the ground through a thin wire. The bonding wire is established using metalized via holes positioned between the patch and the ground plane. These periodic EBG structures establish a high-impedance surface, effectively blocking wave propagation within the bandgap. It is important to note that the substrate' s height should be approximately one-tenth of a wavelength, with vias playing a crucial role in suppressing surface waves within the substrate.

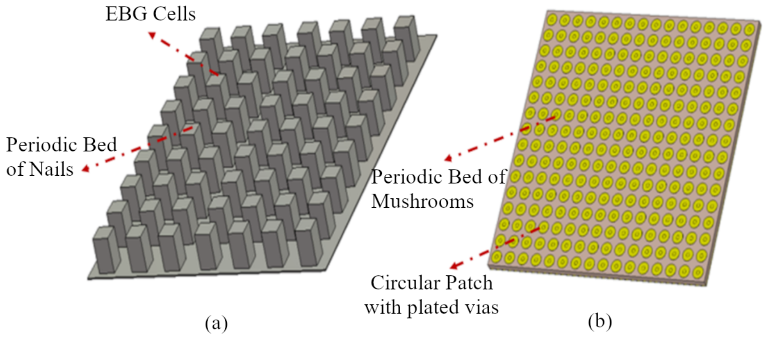

Figure 2. EBG 2-D structures: (**a**) Metallic bed of bails; (**b**) Periodic mushroom cells on PCB substrate

In the domain of waveguide technologies aimed at mm-wave communications, exploring alternatives that complement or surpass the capabilities of ridge gap waveguide (RGW) technology is imperative. Notable contenders among these alternatives include groove gap waveguides (GGWs) and microstrip gap waveguides (MGWs), each offering unique advantages and facing distinct challenges in performance and fabrication [2]. GGW, notable for its ability to support transverse electric (TE) mode propagation and handle higher power levels due to the absence of a ridge, emerges as a promising solution for various microwave components operating within the mm-wave range [12, 13, 14, 15]. Moreover, GGW' s versatility extends to microwave monolithic integrated circuit (MMIC) implementations, further enhancing its appeal and applicability [16, 17]. Conversely, MGW, with a mode propagation similar to RGW but featuring a simplified design process, offers an alternative path. However, the introduction of additional substrate in MGW' s design raises concerns regarding increased size and the introduction of dielectric losses [18, 19]. Despite these challenges, MGW holds promise as a pragmatic solution in specific contexts where ease of design outweighs the drawbacks associated with additional substrate layers. However, the adoption of metallic GW structures, including RGW, presents its own set of challenges. High-precision computer numerical control (CNC) milling is a requisite for their fabrication, a process that can incur significant costs and is subject to stringent fabrication tolerances, particularly within the mm-wave frequency band. These considerations are visually depicted in Figure 3, which illustrates the various GW configurations discussed herein, highlighting the spectrum of design choices and their implications in mm-wave communication systems.

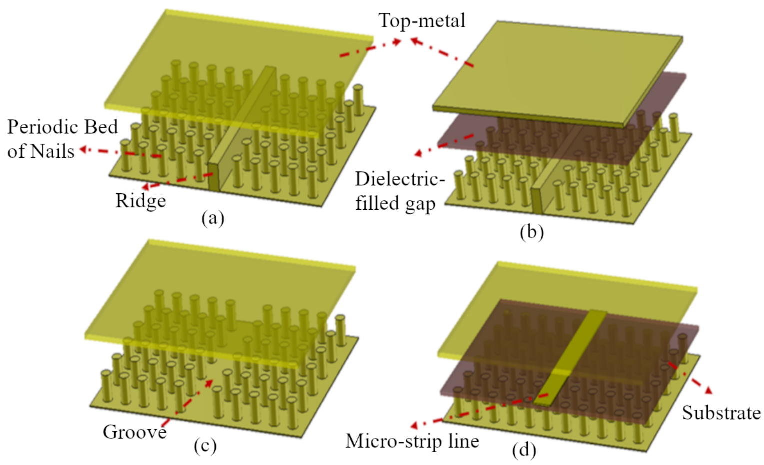

Figure 3. Some possible GW configurations: (**a**) RGW; (**b**) Dielectric-filled RGW; (**c**) GGW; (**d**) MGW

In response to these challenges, the exploration of innovative solutions gains significance. This pursuit of innovation emphasizes the dynamic scope of waveguide technologies and the ongoing quest for enhanced performance and versatility in mm-wave communication systems. Printed ridge gap waveguide (PRGW) technology, for instance, offers alternative approaches. By replacing metallic nails with printed forms or employing a bed of mushrooms while keeping the ridge on the same layer, PRGW offers a more compact form by reducing the number of layers.

2.2 *PGW advantages over traditional waveguide structures*

Expanding on the advantages of PGW over traditional waveguide structures, it is evident that PGW technology offers a multitude of benefits that address key challenges in high-frequency communication systems. By enabling contactless connectivity, PGW structures streamline the integration process, eliminating the complexities associated with intricate wiring and soldering procedures. Moreover, the inherent capability of PGW to suppress surface waves and leakages within defined bandgaps ensures optimal signal propagation and reduced interference, enhancing the overall performance of communication systems. The planar design of PGW not only simplifies fabrication processes but also provides greater design flexibility, facilitating seamless integration into various applications. Furthermore, the low-loss characteristics exhibited by PGW within the mm-wave range enable more efficient signal transmission over extended distances, ensuring reliable communication in demanding environments. Lastly, the compatibility of PGW with packaged MMIC integration highlights its versatility and applicability across diverse communication platforms, including wireless networks, radar systems, and satellite communications [59, 60, 61, 62]. In essence, the advantages offered by PGW position it as a promising solution for advancing high-frequency communication systems, catering to the evolving demands of modern telecommunications.

2.3 *Unit cell analysis of PGW technology*

The unit cell analysis of PGW technology provides valuable insights into its operating principles and performance characteristics [8, 20]. Based on a periodic structure, the PGW effectively creates a stopband, suppressing leakage around the ridge and confining fields above this region. While detailed analyses of cell dimensions and responses are available in the literature, for brevity, they are omitted here. Illustrated in Figure 4a, the designed unit cell features a row of three mushrooms on both sides of the ridge, with periodic boundary conditions enforced on transverse planes to form an infinite-long PGW. Figure 4b presents the dispersion diagram of the PGW unit cell, computed using the CST Microwave Studio's Eigenmode Solver, employing an RO3003 substrate with ε_r of 3 and a thickness of 0.75 mm. The analysis reveals a bandgap, as indicated by the shaded area in Figure 4b, where no mode exists within it, and the modes under the shaded area represent propagating modes. However, eigenmode analysis of the structure demonstrates that the ridge's presence leads to mode propagation within the bandgap region, with additional modes below the shaded area due to the truncation of the periodic structure around the ridge. Notably, the PGW bandwidth aligns with the frequency range of the shaded area covering the unit cell's bandgap. Wave propagation along the ridge supports a Q-TEM mode, indicative of minimal signal dispersion. Table 1 summarizes the unit cell design parameters, providing a comprehensive overview of key specifications essential for PGW performance analysis and optimization.

Table 1. Dimensions of the unit cell

Parameters	Value in (mm)
Height of pin	0.75
Patch width	1.1
Via radius	0.1875
Air gap	0.254
Ridge width	0.9
Via-Via distance	1.6

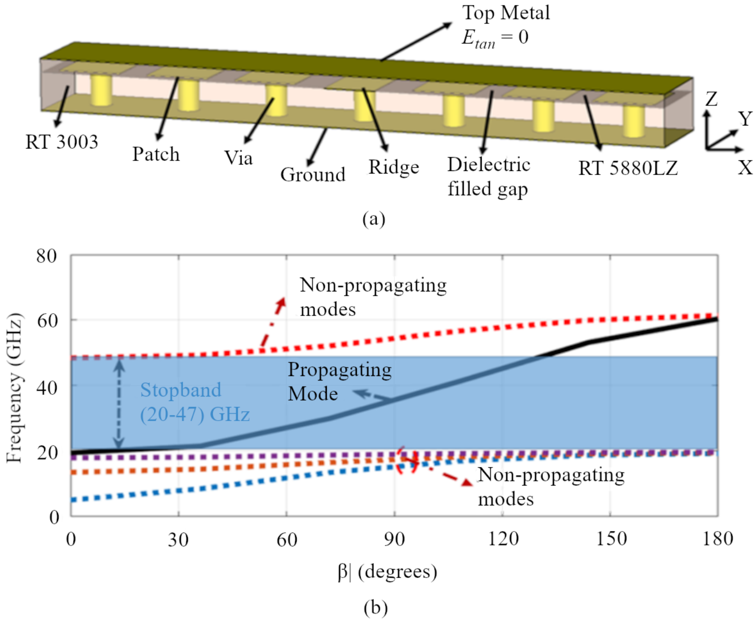

Figure 4. PGW row of unit cell: (**a**) 3-D View; (**b**) Dispersion diagram

3. GW components for beamforming antenna systems

GW technology offers a suite of components essential for the efficient operation of beamforming antenna systems. These components play a vital role in the manipulation and distribution of signals within antenna arrays, enabling precise control over beamforming and radiation characteristics. From power combiners and dividers to phase shifters and crossovers, GW components embody the technological advancements driving the evolution of next-generation communication systems. This section explores the design principles, operational mechanisms, and applications of GW within beamforming antenna systems. Through a comprehensive examination of these components, we uncover the fundamental building blocks underpinning the seamless integration of mm-wave technologies into modern communication infrastructures.

3.1 *MM-Wave antennas with diverse polarizations*

Multiple antennas and antenna feeding structures were deployed using the GW structure, and many techniques were implemented to enhance the system's bandwidth. One notable innovation lies in the utilization of a 4 $\times$ 4 PRGW antenna array featuring a magneto-electric (ME) dipole, strategically designed to achieve unparalleled levels of gain and directional sensitivity [21]. Similarly, a high-gain bow-tie antenna array with integrated grooves has demonstrated exceptional performance metrics, utilizing high-edge diffractions to enhance signal propagation [20]. However, the pursuit of high isolation led to the development of dual-polarized PRGW antennas, albeit at the cost of reduced compactness arising from the utilization of multiple substrates for excitation purposes [22]. The advancements in manufacturing techniques, such as 3-D printing, have aided innovation in mm-wave antenna design. A prime example is the 3-D printed dielectric polarizer, coupled with a PRGW ME dipole antenna, which showcases remarkable gains of up to 20 dBi with a 6.5% axial ratio bandwidth [23]. Meanwhile, slot antenna arrays, renowned for their utility in radar and communication applications, have undergone significant enhancements to address inherent bandwidth limitations. Innovative solutions, including T-junction deployments and cavity integrations, have been instrumental in widening bandwidth and augmenting directivity [5, 6, 7, 24]. Moreover, the integration of multilayer substrate-integrated gap waveguide (SIGW) horn antennas and hybrid technologies amalgamating SIW and PRGW have expanded the design horizons of mm-wave antennas. By leveraging elevated-SIGW structures and triangular slot configurations, engineers have achieved wide bandwidth coverage and enhanced gain performance, paving the way for novel applications in diverse scenarios [25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44]. Illustrating the breadth of possibilities, Figure 5 showcases metallic GW antennas tailored to various mm-wave applications, addressing specific requirements and challenges. Complementing this, Figure 6 exhibits antennas based on PGW technologies, emphasizing the versatility and adaptability of GW components in the intricate landscape of beamforming antenna systems. Table 2 summarizes the performance evaluation of antenna structures with different GW technologies.

From Table 2, it is evident that nearly all possible GW structures, encompassing both metallic and PCB configurations, are represented. Metallic GWs necessitate high-precision CNC milling, and for designs requiring higher power levels, opting for the metallic GW structure is recommended, as it can handle more power compared to PGW structures. PGW structures are low-profile, limiting their capacity to handle high power. There exist two distinct metallic GW structures: GGW and RGW. The primary disparity between these structures lies in the presence of a ridge; GGW lacks a ridge, rendering its propagating mode akin to the rectangular waveguide. Due to the absence of a ridge, GGW can manage higher power levels compared to RGW.

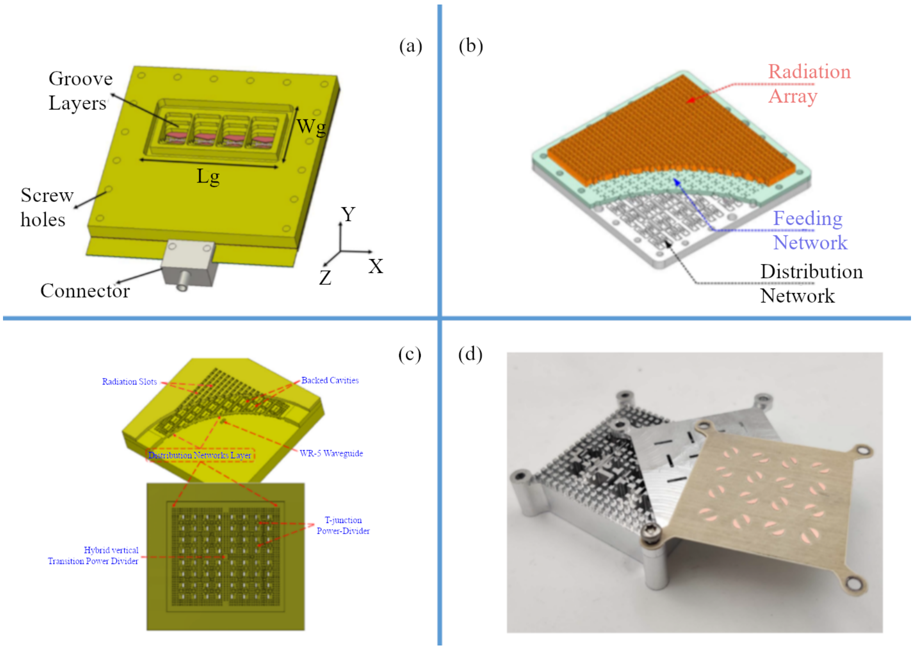

Figure 5. Various metallic GW antenna configurations in the mm-wave spectrums: (**a**) RGW loaded with grooves [20]; (**b**) RGW 32 × 32 antenna array [6]; (**c**) 16 × 16 RGW distribution network antenna [35]; (**d**) Fabricated SATCOM GW circularly polarized antenna array [34]

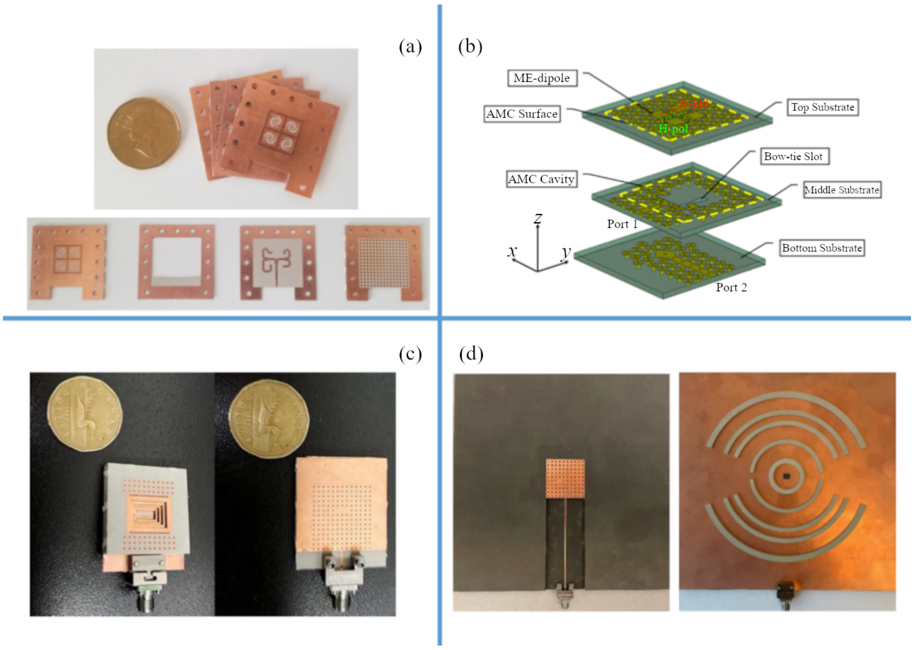

Figure 6. PGW antenna structures: (**a**) 2 × 2 CP spiral-shaped PRGW antenna array [43]; (**b**) Dual-polarized high-isolation PRGW ME dipole antenna [22]; (**c**) SIGW multilayer pyramidal horn antenna [25]; (**d**) PRGW antenna utilizing diffracted fields from semi-ring shaped dielectric edges [31].

In the mm-wave range, surface roughness or imperfect flatness poses a common problem, potentially creating gaps between substrates that result in leakages. Specifically, stacking multiple dielectric substrates can inadvertently create such gaps due to surface roughness, a challenge often overlooked by engineers aiming for cost reduction when designing mm-wave devices with multilayers of substrates. A proposed solution involved a five-layered stacked horn using SIW technology to address cost concerns. However, a notable deviation between measured and simulated radiation patterns arose from the combined effects of inaccuracies in the roughness tolerances of the horn walls, which consist of metalized via holes [74]. To offer a practical remedy for surface roughness, a PEC-AMC configuration can be employed to suppress leakage between substrates in multilayer devices. Additionally, several antenna structures have been proposed to support various applications using microstrip line technology in the mm-wave range and beyond [75, 76, 77, 78, 79, 80, 81, 82, 83, 84, 85]. However, they often experience significant performance deterioration due to surface waves, high dielectric losses, and leakages in the mm-wave spectrum.

Table 2. Comparison between different antenna structures with GW technology

Ref	Freq.	Technology	BW	Gain	Efficiency	Total Layers
[5]	28 GHz	RGW cavity slot array	27%	26.2 dBi	60%	3
[7]	60 GHz	RGW antenna array	30%	27.5 dBi	80%	3
[9]	30 GHz	PRGW ME dipole	20%	10.3 dBi	85%	3
[18]	10 GHz	Inverted MGW dual-mode horn	10%	24.5 dBi	NA%	3
[20]	30 GHz	PRGW horn antenna	25%	16.5 dBi	87%	6
[21]	30 GHz	PRGW ME dipole	16%	21 dBi	70%	4
[22]	30 GHz	PRGW dual polarized ME dipole	20%	12 dBi	80%	5
[24]	13.5 GHz	RGW linear array	20%	12.5 dBi	NA	2
[25]	30 GHz	SIGW horn antenna	20.5%	11.5 dBi	89%	6
[27]	60 GHz	AMC packaged SIW cavity	12%	32 dBi	80%	4
[28]	32 GHz	SIGW dual-polarized	12.5%	13 dBi	88%	3
[29]	30 GHz	SIGW CP MIMO	14.5%	7.8 dBi	90%	3
[31]	20 GHz	PRGW with dielectric rings	12%	20.5 dBi	87%	4
[34]	29 GHz	GGW	14%	19.2 dBi	85%	3
[43]	30 GHz	PRGW Spiral Antenna Array	27%	12.3 dBi	88%	4

3.2 *Power combiners and dividers, crossovers, and phase shifters*

Power dividers serve as indispensable components within beamforming antenna systems, enabling precise control over how signals are distributed and beam shaping across diverse directions. In mm-wave communications, where efficiency and precision are critical, the functionality and design of power dividers become crucial aspects of system performance. In a recent study [45], researchers introduced a reconfigurable power divider leveraging metallic RGW technology as highlighted in Figure 7. This innovative design enables precise control over power splitting ratios, a pivotal requirement for efficient beamforming. The power divider is constructed across three layers, integrating various components such as metallic sheets with strategically positioned apertures for signal coupling. Two slits are drilled on the metallic sheet to move the sheet, similar to a cantilever, through screws from the bottom to bend the sheet upwards. The mechanism is buried inside the EBG cells, where electromagnetic fields are negligible, taking advantage of the GW structure to demonstrate exceptional performance with a notable 44.4% bandwidth and commendable matching levels. In parallel, advancements in multilayer GW technology have led to the development of power dividers [46] capable of uniform power division across a spectrum of output phases, ranging from 0° to 180°. The design capitalizes on the unique layer configurations inherent to MGW structures, enabling the seamless integration of multiple transformers and stubs. This arrangement ensures precise phase adjustments while maintaining periodicity and adapting slot dimensions to optimize functionality. The resulting power dividers exhibit remarkable versatility, catering to a diverse array of beamforming requirements across mm-wave communication systems.

Quadrature hybrid couplers are pivotal components within beamforming networks, providing essential functionality for equal power division with a 90° phase difference—a fundamental requirement for beam scanning and steering in advanced antenna arrays. Moreover, the cascading of two quadrature hybrid couplers gives rise to crossovers, pivotal elements in beamforming networks, enabling seamless signal distribution and manipulation. Figure 8 provides a comprehensive overview of aperture coupling and crossovers realized using various GW technologies. In a recent study [47], researchers demonstrated the implementation of quadrature hybrid coupling through a planar patch coupler employing PRGW technology. Applying multi-step matching transformers, the patch coupler ensures enhanced coupling and phase levels across a wide operational bandwidth. Building upon this foundation, subsequent research [48] introduced tapered transformers, optimizing the bandwidth for 20% operation. Expanding the horizons of quadrature hybrid coupling, [49] introduced a patch coupler featuring perpendicular outputs, achieved through strategic asymmetrical cuts to the patch's edges. Similarly, [50] showcased a circular patch with a central slot, enabling coupling to two perpendicular planar outputs. Notably, a novel metasurface replaces the upper ground, introducing reconfigurable coupling levels by rotating the metasurface at varying angles—a testament to the adaptability of PRGW technology. In [51], multilayer backward coupling is achieved using a single slot in PRGW technology, augmenting matching levels and operational bandwidth. Meanwhile, [52, 53] proposed a planar and multilayer crossover utilizing PGW, respectively, employing cascaded quadrature hybrid couplers and further optimizing performance to enhance functionality while reducing size. Innovations extend to [54], where a PRGW 0-dB coupler was realized through modifications to the rectangular patch, enhancing wave propagation to a single port through tapered cuts. In a parallel research, [55] utilized GGW technology to craft a coupler based on multi-hole coupling at V-band, leveraging rectangular holes with chamfered edges to achieve superior matching and isolation levels. Similarly, [56] explored RGW technology to design a multilayer coupler, employing apertures to achieve varying coupling levels—a proof to the versatility and adaptability of GW technologies in advancing beamforming networks and mm-wave communication systems. Transitioning from power distribution components, the discussion now extends to the critical role of phase shifters in beamforming networks, contributing to the dynamic control and manipulation of signal phase and amplitude within antenna arrays. The performance of the reported couplers is summarized in Table 3, showcasing their effectiveness and advancements in mm-wave communication systems.

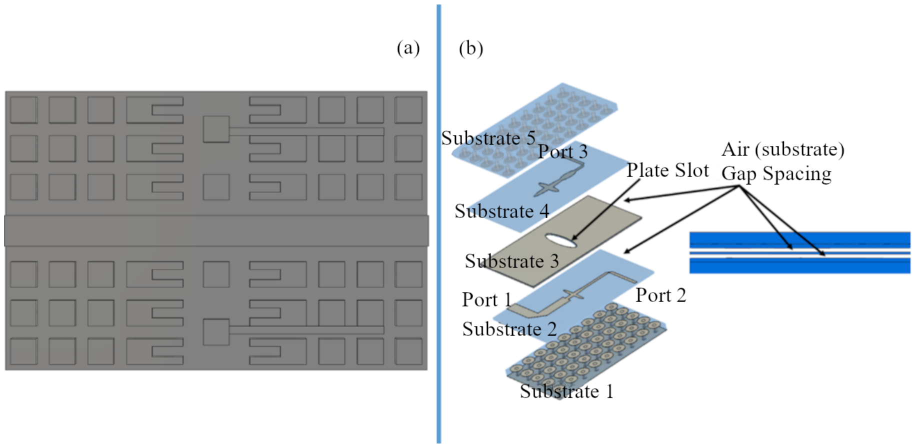

Figure 7. (**a**) Reconfigurable RGW power splitter [45]; (**b**) MGW power dividers with different phase outputs [46]

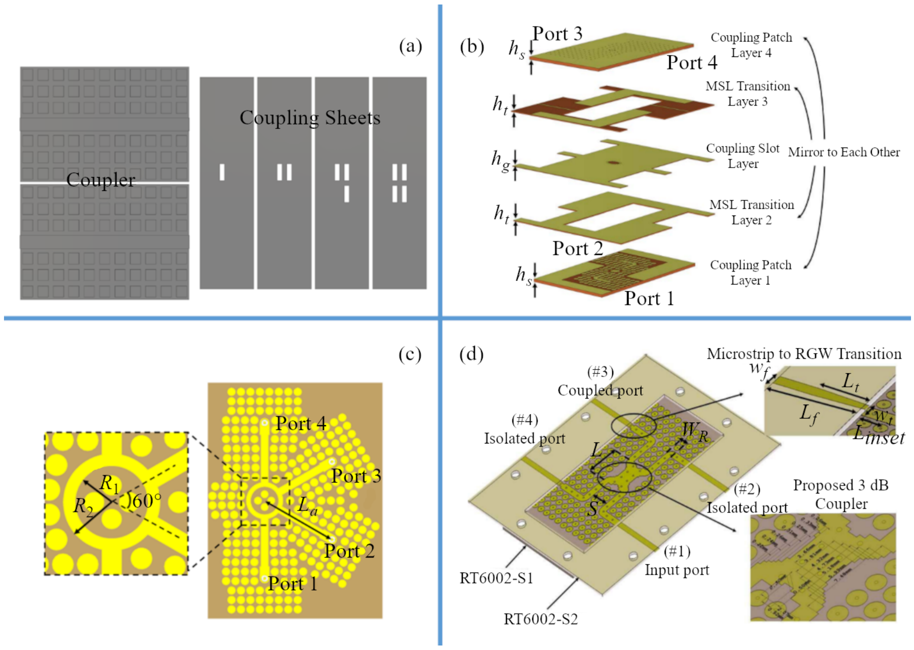

Figure 8. (**a**) RGW aperture coupler with interchangeable coupling sheets [56]; (**b**) PRGW multilayer backward-wave coupler [51]; (**c**) PRGW differential rat-race coupler [53]; (**d**) PRGW crossover [52]

Table 3. Comparison between different GW couplers

Ref.	Technology	Center Freq.	Bandwidth	Type
[47]	PRGW	30 GHz	6%	Planar 3-dB 90°
[48]	PRGW	30 GHz	26.5%	Planar 3-dB 90°
[49]	PRGW	30 GHz	26.5%	Planar 3-dB 90°
[50]	SIGW	14.4 GHz	34.45%	Planar Reconfigurable
[51]	PRGW	30 GHz	38%	Multilayer 3-dB 90°
[52]	PGW	30 GHz	13.3%	Planar 0-dB
[54]	PRGW	30.5 GHz	6.5%	Planar 0-dB
[55]	GGW	60 GHz	33.3%	Multilayer 10-, 20-, 30-dB
[56]	RGW	18.5 GHz	40%	Multilayer 3-dB 90°

Phase shifters are vital components in beamforming networks, offering precise control over the phase difference among outputs connected to antenna arrays. This control enables the manipulation of beam shape and direction by adjusting the progressive phase shift and amplitude. Various implementations of phase shifters utilizing GW technology are depicted in Figure 9, showcasing their versatility and effectiveness in mm-wave applications. One notable implementation, detailed in [63], introduces a Schiffman phase shifter with a wideband operation using PRGW technology. This design strategically alters the layout of EBG cells to accommodate a bent shape, thereby ensuring maximum suppression of leakage and enhancing performance. In a different approach, [64] utilizes delay lines within a multilayer GW Butler matrix to achieve precise phase shifts of 0° and 45° relative to the crossover. Integrated stubs ensure coherent phase behavior across a wider bandwidth, enhancing the system's operational efficiency. Furthermore, [65] presents a multilayer MGW phase shifter relative to a line loaded with stubs in a Butler matrix, offering versatility for higher-order Butler matrices through variations in patch dimensions. A different design approach is explored in [66], where a RGW phase shifter design features a glide-symmetric ridge with successive semi-circle bends optimized for wideband operation at mm-wave frequencies. Utilizing dielectric slabs above the RGW ridge, [67] introduces phase shifts relative to a reference line, enhancing matching and phase balance through tapered cuts. A simple H-plane bent phase shifter design using GGW technology is proposed in [68], albeit with limited phase balance across a narrow band. Lastly, [69] presents a mechanically tunable GGW phase shifter operating at the ku-band. It integrates a metallic strip affixed to the side wall with a tuning screw, allowing for phase shifts of up to 540° with low insertion loss levels. These diverse implementations highlight the adaptability and effectiveness of GW-based phase shifters in modern mm-wave communication systems.

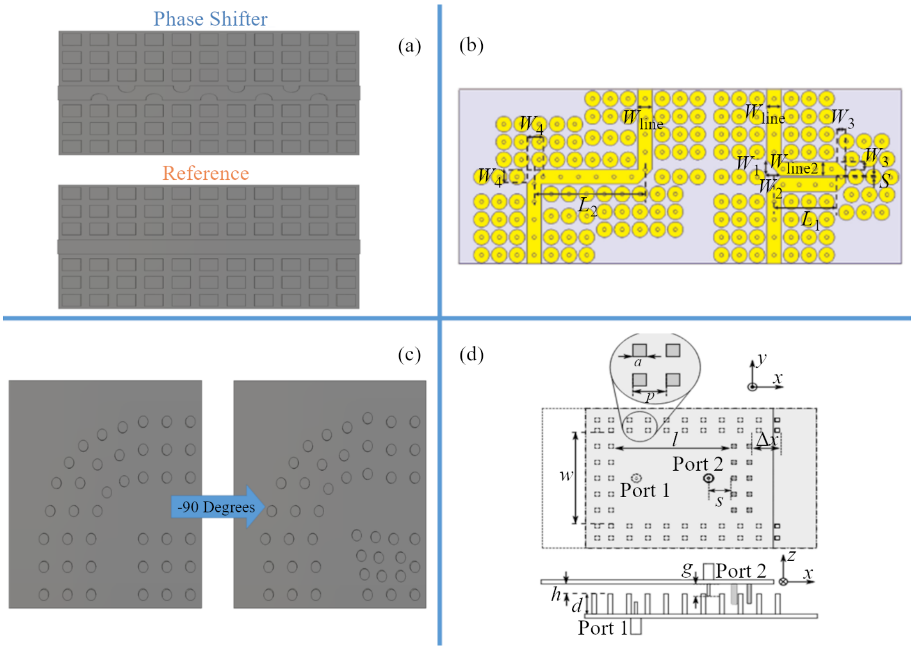

Figure 9. (**a**) RGW glide-symmetric phase shifter [66]; (**b**) PRGW Schiffman phase shifter [85]; (**c**) GGW 90° H-plane phase shifter [68]; (**d**) GGW mechanically tuneable phase shifter [69].

4. GW beamforming antenna systems

GW beamforming antenna systems rely on a complex arrangement of components to precisely control the phase and amplitude of incoming signals, shaping the direction and characteristics of emitted beams. Figure 10 showcases the diversity of GW technologies and topologies employed in these systems. In a study by [70], a wideband Butler matrix operating at the Ka-band is introduced, utilizing the capabilities of PRGW technology. This innovative network integrates wideband designs for quadrature 3-dB couplers and a Schiffman phase shifter, enabling precise end-fire beam switching across a remarkable 21.25% bandwidth. Despite its ground breaking functionality, one notable limitation of this approach lies in the considerable circuit size required for its implementation. A contrasting strategy is unveiled in [64], where metallic artificial magnetic conductor packaging, manifested in the form of EBG nails, envelops a microstrip Butler matrix. This shielding mechanism not only protects the system against external electromagnetic interference but also limits signal leakage. Moreover, the compact design of couplers and phase shifters, coupled with close component placement, minimizes the overall size of the system. Further advancements are witnessed in [65], where multilayer Butler matrix layouts, powered by multilayer GW technology at the KA-band, revolutionize beamforming networks. These layouts, adaptable for any N $\times$ N order, reduce the overall size by half, while multilayer transitions apply the necessary phase shifts, facilitating broadside beam switching. Diving deeper into innovation, [9] introduces ME dipole antennas fed by a 2-D scanning Butler matrix, designed using PRGW technology. This configuration, integrated with quadrature hybrid couplers and optimized matching, achieves a compact size without compromising network efficiency. Furthermore, [71] unveils dual-polarized scanning beams, achieved by duplicating the network and introducing orthogonal layers for differential feeding. This ingenious setup allows the antenna to be excited with both polarizations. At the W-band, [68] showcases a modified Butler matrix, applied by GGW technology. Employing 90° phase shifters and 3-dB couplers, this network conjures sum and difference patterns with precision, applicable to a spectrum of applications. Concurrently, a traditional Butler matrix designed using GGW technology for the Ka-band and enhanced by a 2 $\times$ 2 subarray to amplify gain is proposed in [72]. In summary, GW beamforming antenna systems offer more diverse architectures and technologies to address the multifaceted demands of mm-wave communication. In summary, GW beamforming antenna systems offer a wide array of architectures and technologies to meet the multifaceted demands of mm-wave communication. From wideband Butler matrices leveraging PRGW technology to innovative approaches like metallic artificial magnetic conductor packaging and multilayer Butler matrix layouts, each solution addresses specific challenges while pushing the boundaries of performance and compactness. These advancements underscore the versatility and adaptability of GW technology in enabling precise control over signal directionality and characteristics. Table 4 provides a comprehensive overview of the reported beamforming networks, showcasing the breadth of innovation in this field.

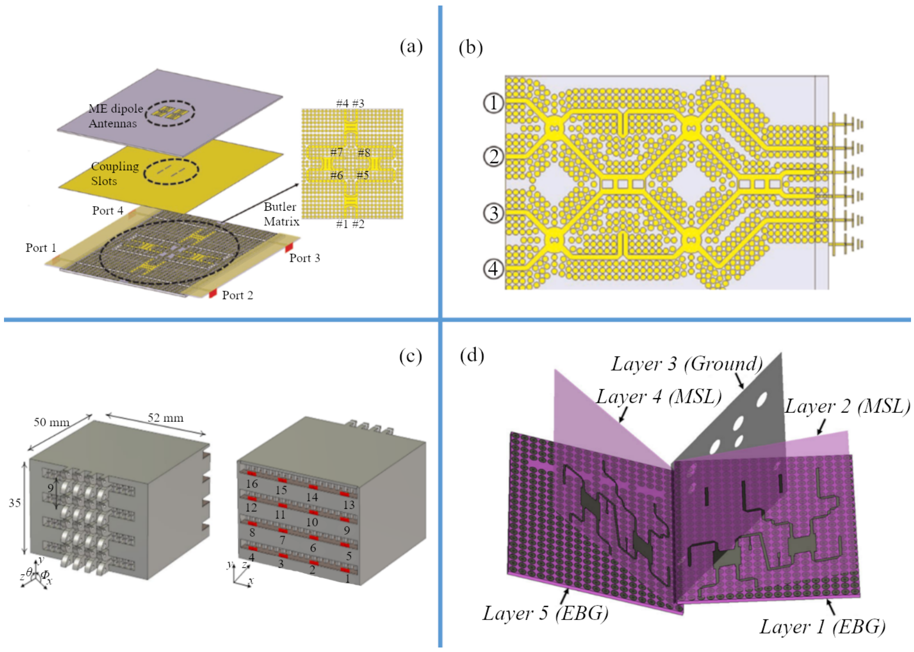

Figure 10. (**a**) W-band GGW Butler matrix [85]; (**b**) Wideband PRGW Butler matrix [85]; (**c**) Metallic-packaged microstrip Butler matrix [64]; (**d**) Multilayer packaged microstrip Butler matrix [65].

Table 4. Comparison between different beamforming networks

Ref.	Technology	Center Freq.	Bandwidth	Type
[70]	PRGW	30 GHz	21.25%	Semilog periodic dipole array fed by planar Butler matrix
[64]	PGW	30 GHz	16.7%	Horn array fed by planar Butler matrix
[65]	PGW	29 GHz	13.8%	Slot array fed by Multilayer Butler matrix
[9]	PRGW	30 GHz	20%	2-D scanning ME dipole antenna
[71]	PRGW	30 GHz	10%	Dual-polarized 2-D scanning ME dipole antenna
[68]	GGW	94 GHz	0.7%	Planar modified Butler matrix
[72]	GGW	28 GHz	12.1%	Slot sub-arrays fed by planar Butler matrix

5. Future trends and implications

GW has demonstrated tremendous capability in supporting RF devices in the mm-wave range and beyond. In future endeavors, GW could be implemented to bolster full-duplex antenna systems for radar applications in the mm-wave spectrum. Some circulators have already been designed based on GW technology [88, 89]. Integrating circulators and antennas in a single layer could streamline fabrication complexities and enhance performance. Additionally, active antennas equipped with power amplifiers (PA) and low-noise amplifiers (LNA) could be realized based on GW technology in both transmitters (TX) and receivers (RX) [90, 91, 92]. Given that GW is a packaged device, it holds promise for designing future transceiver systems based on MEMS or CMOS technology. Moreover, high-power radial combiners and isolated power combiners could be implemented with GW technology [93]. Furthermore, ongoing efforts could explore expanding or manipulating the stop-band of the EBG cell [94], paving the way for enhanced performance and versatility in RF applications.

In anticipation of future advancements, the trajectory of GW technology is undergoing a transformative shift, driven by the relentless pursuit of enhanced performance and expanded functionality across various applications in mm-wave communication. Central to this evolution is the persistent drive towards miniaturization and integration. As the demand for compact and lightweight systems escalates, researchers are exploring innovative methodologies to condense complex GW components without compromising performance. The convergence of advanced manufacturing techniques and materials science promises to unlock unprecedented levels of integration, facilitating streamlined and efficient mm-wave communication systems. Moreover, the demand for higher data rates and broader bandwidths remains continuous. Future research endeavors are set to explore novel strategies for enhancing bandwidth efficiency while mitigating signal distortions and losses. From advanced waveguide designs to innovative signal processing algorithms, the pursuit of wider bandwidths holds profound implications for realizing ultra-fast and reliable communication networks. Beamforming, a crucial element of modern mm-wave communication systems, enables precise control over signal propagation and reception. Emerging trends in GW technology are bound to witness the rise of advanced beamforming techniques, leveraging machine learning algorithms and adaptive signal processing methodologies. These cutting-edge approaches allow beamforming efficiency, enabling dynamic adaptation to changing environmental conditions and user demands. Furthermore, seamless integration with emerging technologies stands as a key enabler for unlocking new use cases and applications. From the Internet of Things (IoT) to autonomous vehicles and beyond, GW technology serves as a foundation for enabling seamless connectivity and data exchange across diverse platforms and domains. However, alongside these transformative benefits, critical considerations around privacy, security, and ethical implications warrant careful scrutiny and proactive mitigation strategies.

6. Conclusions

In conclusion, this review paper has provided a comprehensive overview of GW technology within the band of mm-wave communication systems. Through an exploration of various components, including power dividers, couplers, phase shifters, and beamforming networks, we have explored the details of GW technology and its pivotal role in enabling high-performance communication systems. The discussion has highlighted the versatility, efficiency, and promise of

GW technology in addressing the evolving demands of mm-wave communication. From its ability to support diverse polarization schemes to its role in facilitating beamforming and signal manipulation, GW technology emerges as the basis of modern wireless communication infrastructure. Moreover, the review has highlighted ongoing research efforts and emerging trends that are bound to shape the future trajectory of GW technology. From advancements in miniaturization and integration to the exploration of novel beamforming techniques and the integration with emerging technologies, however, even with the potential of GW technology, it is imperative to acknowledge the challenges and considerations. From addressing issues of signal loss and distortion to ensuring robust security and privacy measures, the continued advancement of GW technology requires effort from researchers. As we navigate the complexities of mm-wave communication, GW technology stands to play a central role in shaping the future of wireless connectivity and providing seamless communication and connectivity. This review paper serves as an indication of the transformative potential of GW technology and its impact on the future of mm-wave communication systems.

Conflict of interest

There is no conflict of interest for this study.

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