

Millimeter-Wave Technology Based Applications Across Industries

Ud. Chowdhury^{1*}, Sohag Chakma²

^{1,2}Department of Electrical and Electronic Engineering, International Islamic University Chittagong, Chittagong 4318, Bangladesh

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ABSTRACT

In the vast spectrum of wireless communication, millimeter-wave (mmWave) technology emerges as a game-changer, promising to revolutionize connectivity and enable a myriad of applications across diverse industries. Operating in the frequency range between 30 GHz and 300 GHz, mmWave offers immense bandwidth and high-speed data transmission, making it ideal for applications that demand high capacity and low latency. In this comprehensive exploration, we delve into the multifaceted applications of mmWave technology, its impact on various sectors, and the transformative innovations it heralds.

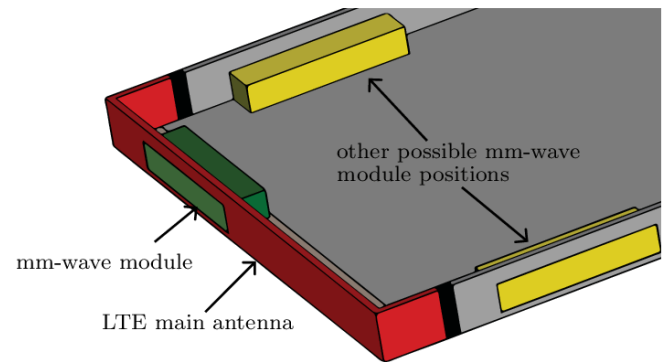
Author's e-mail: ud.chowdhury@gmail.com, soh_Chakma@gmail.com

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UNDERSTANDING MILLIMETER-WAVE TECHNOLOGY

Millimeter-wave technology represents a paradigm shift in wireless communication, offering unprecedented data rates and transmission capabilities. Operating at frequencies higher than those traditionally used for wireless communication, mmWave technology harnesses the unique properties of short wavelengths and wide bandwidths to enable high-capacity data transmission over short distances. By leveraging advanced modulation schemes, beamforming techniques, and antenna technologies, mmWave systems achieve remarkable throughput and reliability, paving the way for a wide range of applications across industries.^[1-19] Millimeter-wave technology refers to the use of electromagnetic waves with frequencies ranging from 30 to 300 gigahertz (GHz), corresponding to wavelengths between 1 and 10 millimeters. This high-frequency spectrum offers several advantages for various applications, including wireless communication, imaging, and sensing as in Fig. 1.

In wireless communication, millimeter-wave technology enables high-speed data transmission over short distances with low latency. By utilizing a large available bandwidth, millimeter-wave communication systems can achieve multi-gigabit data rates, making them ideal for applications such as 5G cellular networks, point-to-point wireless links, and wireless backhaul [20]-[33]. In addition to communication, millimeter-wave technology has applications in imaging and sensing. Millimeter-wave



imaging systems can penetrate through materials such as clothing, plastic, and drywall, making them suitable for security screening, medical imaging, and industrial inspection. Millimeter-wave sensors can detect and measure various physical parameters, including temperature, humidity, and gas concentration, making them valuable for environmental monitoring, automotive safety systems, and industrial process control as in Fig. 2.

Overall, millimeter-wave technology offers promising opportunities for advancing wireless communication, imaging, and sensing capabilities, with potential applications in diverse industries such as telecommunications, healthcare, transportation, and manufacturing. Continued research and development efforts are expected to further enhance the performance and applicability of millimeter-wave technology in the years to come.^[34-39]

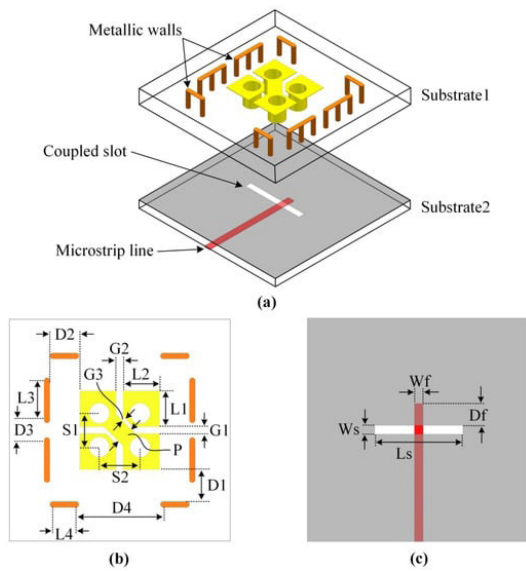


Fig. 2: Polarized Magneto-Electric Dipole Antenna

APPLICATIONS OF MILLIMETER-WAVE TECHNOLOGY

1. 5G Wireless Networks

5G wireless networks represent one of the most prominent applications of mmWave technology, ushering in a new era of connectivity and communication. By leveraging mmWave frequencies, 5G networks deliver ultra-fast data speeds, low latency, and high network capacity, enabling a wide range of innovative services and applications. MmWave 5G networks support applications such as high-definition video streaming, virtual reality, augmented reality, and real-time gaming, transforming the way we experience and interact with digital content. [40-46] 5G wireless networks represent the fifth generation of cellular network technology, offering significant advancements over previous generations in terms of speed, capacity, latency, and connectivity. With 5G, data rates can reach multi-gigabit speeds, enabling ultra-fast download and upload speeds, seamless streaming of high-definition video, and real-time interactive applications.

One of the key features of 5G is its use of millimeter-wave frequencies, which offer a large available bandwidth for high-speed data transmission. By leveraging millimeter-wave technology, 5G networks can achieve higher data rates and lower latency compared to previous generations, making them ideal for applications such as augmented reality, virtual reality, and autonomous vehicles as in Fig. 3. 5G also introduces network slicing, which allows operators to create virtualized, customized network instances tailored to specific applications or user requirements. This enables more efficient use of network resources and better support for diverse use cases, ranging from massive machine-type communication to ultra-reliable low-latency communication. [47-52]

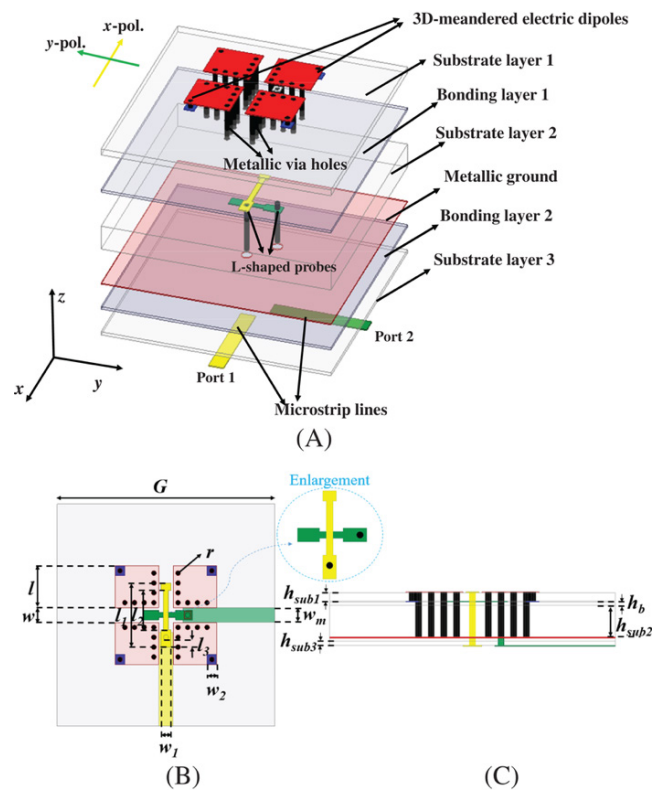


Fig. 3: Dual-polarized ME-dipole antenna

Additionally, 5G networks support massive device connectivity, enabling the Internet of Things (IoT) and the proliferation of connected devices and sensors. This opens up new opportunities for smart cities, industrial automation, and remote monitoring applications. [53-57] Overall, 5G wireless networks promise to revolutionize communication, connectivity, and digital innovation, ushering in a new era of connectivity and enabling transformative applications and services across various industries and sectors.

2. Wireless Backhaul and Fronthaul:

MmWave technology is increasingly being used for wireless backhaul and fronthaul solutions in telecommunications networks. MmWave links provide high-capacity, low-latency connectivity between base stations, data centers, and network hubs, enabling efficient data transport and network optimization. MmWave backhaul and fronthaul solutions support the expansion of 5G networks, enabling seamless connectivity in urban, suburban, and rural areas as in Fig. 4.

Wireless backhaul and fronthaul are critical components of modern telecommunications networks, providing the infrastructure for connecting remote base stations and cell sites to the core network. These technologies play a vital role in enabling high-speed data transmission, supporting the increasing demand for mobile broadband

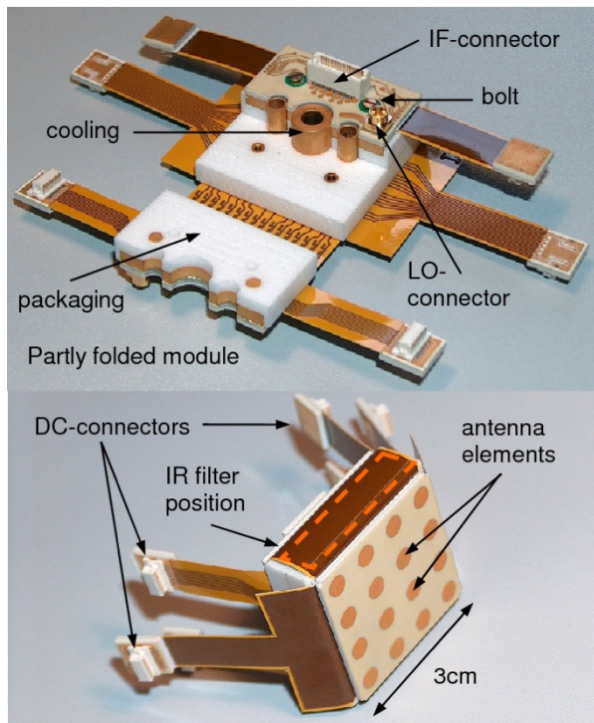


Fig. 4: RF and Millimeter-wave Antennas

services, and facilitating the deployment of advanced wireless technologies such as 5G.

Wireless backhaul refers to the transmission of data between the core network and remote base stations or cell sites, typically over long distances. It serves as the backbone of the mobile network, carrying large volumes of traffic from the access network to the core network for processing and routing. Wireless backhaul solutions include microwave links, millimeter-wave links, and satellite links, offering high-capacity, low-latency connectivity to support the growing demand for mobile data services. Fronthaul, on the other hand, refers to the transmission of data between remote radio units (RRUs) and baseband units (BBUs) within a cell site or base station. Fronthaul links connect the antennas and radio equipment at the cell site to the centralized processing and control units, enabling coordinated operation and signal processing. Fronthaul solutions include fiber-optic links and wireless links using technologies such as Ethernet or CPRI (Common Public Radio Interface), providing high-speed, low-latency connectivity to support the deployment of advanced wireless technologies such as cloud radio access networks (C-RAN) and massive MIMO (Multiple Input Multiple Output) systems.

Together, wireless backhaul and fronthaul technologies form the backbone of modern telecommunications networks, enabling high-speed, reliable connectivity and supporting the delivery of advanced wireless services to users worldwide as in Fig. 5.

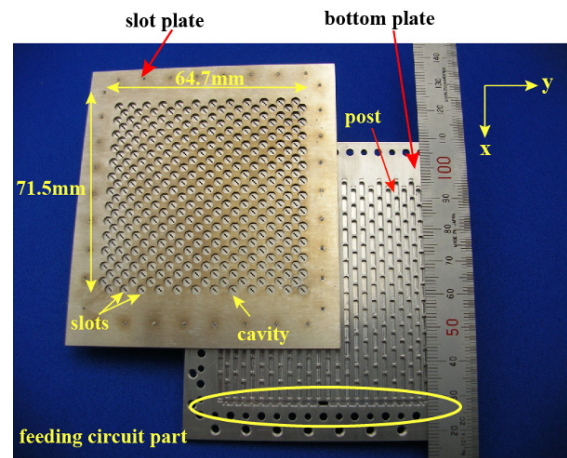


Fig. 5: High-Gain Millimeter-Wave Planar Array Antennas

3. Fixed Wireless Access (FWA):

MmWave technology is revolutionizing the delivery of broadband internet access through fixed wireless access (FWA) solutions. FWA deployments leverage mmWave frequencies to deliver high-speed internet connectivity to homes, businesses, and communities without the need for traditional wired infrastructure. MmWave FWA solutions offer gigabit-speed internet access, enabling broadband connectivity in underserved and remote areas and bridging the digital divide.

Fixed Wireless Access (FWA) is a wireless communication technology that provides high-speed internet access to fixed locations, such as homes, businesses, and rural areas, using wireless connections instead of traditional wired infrastructure. FWA enables broadband connectivity in areas where laying fiber or cable infrastructure is impractical or cost-prohibitive. FWA systems typically utilize radio frequency (RF) signals to establish point-to-point or point-to-multipoint connections between a central base station and customer premises equipment (CPE) installed at user locations. The base station, often located on a tall structure or tower, serves as the hub of the FWA network, transmitting and receiving data to and from multiple customer locations within its coverage areas as in Fig. 6.

FWA offers several advantages over wired broadband technologies, including faster deployment, lower infrastructure costs, and greater flexibility in network expansion. By leveraging wireless connections, FWA providers can quickly deploy broadband services to underserved or rural areas, bridging the digital divide and bringing high-speed internet access to areas without access to traditional wired infrastructure. FWA technology continues to evolve, with advancements in wireless standards such as 5G and Wi-Fi 6 enabling

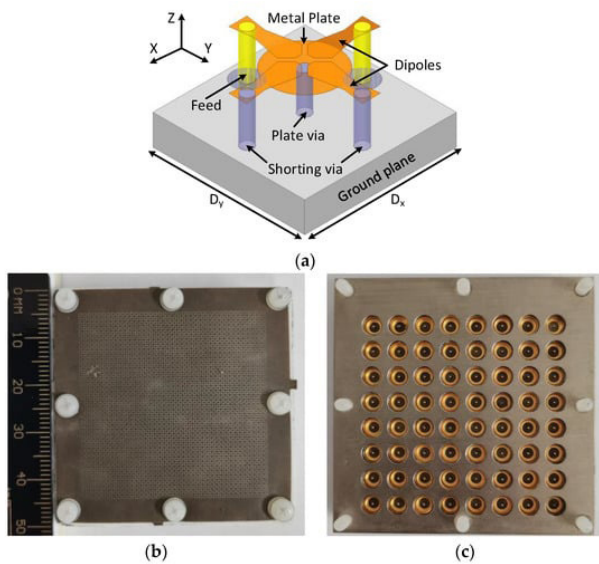


Fig. 6: Millimeter-Wave Antennas and Devices

higher data rates, lower latency, and improved network performance. As a result, FWA is becoming an increasingly viable option for delivering high-speed broadband services to homes and businesses worldwide, offering an alternative or complementary solution to traditional wired broadband technologies.

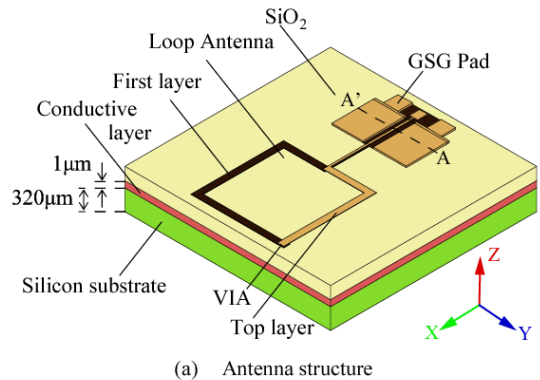
4. Automotive Radar and Sensing

MmWave technology plays a crucial role in automotive radar and sensing systems, enabling advanced driver assistance systems (ADAS) and autonomous driving technologies. MmWave radar sensors provide high-resolution, long-range detection capabilities, allowing vehicles to detect and track objects, pedestrians, and other vehicles with precision and accuracy. MmWave radar technology enhances safety, situational awareness, and collision avoidance in automotive applications.

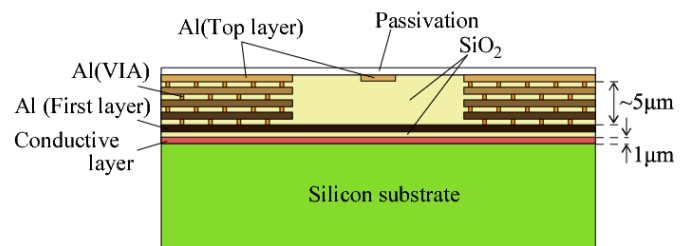
Automotive radar and sensing systems are critical components of advanced driver assistance systems (ADAS) and autonomous vehicles, enabling vehicles to perceive their surroundings and react to potential hazards in real-time. These systems utilize radar technology to detect objects, obstacles, and other vehicles on the road, providing essential information for collision avoidance, adaptive cruise control, and automated driving functions as in Fig. 7.

Automotive radar systems typically operate in the microwave frequency range and employ radar sensors mounted on the vehicle's exterior to transmit and receive radio frequency signals. These radar sensors use techniques such as frequency modulation and pulse compression to accurately measure the distance, speed, and relative motion of nearby objects. One of the key

ports [4].



(a) Antenna structure



Gain Enhancement Of Millimeter-Wave On-Chip Antenna

advantages of automotive radar systems is their ability to operate effectively in adverse weather conditions, such as rain, fog, and snow, where other sensing technologies may struggle. Radar sensors can penetrate through obstacles and provide reliable detection capabilities even in low visibility conditions, enhancing vehicle safety and reliability.

In addition to collision avoidance and adaptive cruise control, automotive radar systems are also used for other applications such as blind spot detection, lane change assistance, and pedestrian detection. As automotive radar technology continues to evolve, with advancements in sensor design, signal processing algorithms, and integration with other sensing modalities, it holds the potential to further improve vehicle safety, efficiency, and autonomy.

5. Wireless Gigabit Connectivity

MmWave technology enables wireless gigabit connectivity for a wide range of applications, including indoor and outdoor wireless networks, enterprise networking, and consumer electronics. MmWave gigabit wireless solutions offer ultra-fast data speeds, low latency, and reliable performance, enabling seamless connectivity for high-bandwidth applications such as video streaming, cloud computing, and virtual reality.

Wireless Gigabit connectivity refers to high-speed wireless communication technologies capable of

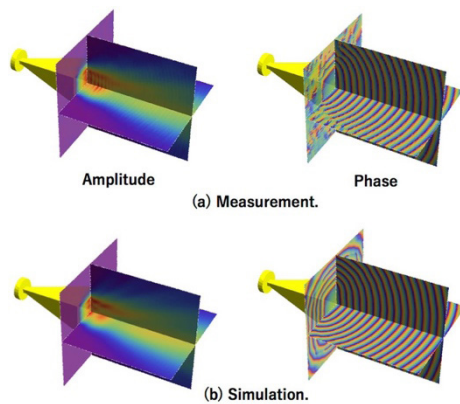


Fig. 8: Amplitude and phase distribution of the mm-wave

transmitting data at gigabit-per-second (Gbps) speeds, enabling fast and reliable wireless connectivity for a wide range of applications. These technologies leverage the unlicensed 60 GHz frequency band, also known as the millimeter-wave band, to achieve multi-gigabit data rates over short distances as in Fig. 8.

One of the key technologies enabling wireless Gigabit connectivity is IEEE 802.11ad, commonly known as WiGig. WiGig operates in the 60 GHz frequency band and supports data rates of up to 7 Gbps, making it suitable for high-bandwidth applications such as ultra-high-definition video streaming, virtual reality, and wireless docking. WiGig utilizes beamforming and directional antennas to achieve robust and efficient communication, even in crowded wireless environments. Another technology driving wireless Gigabit connectivity is the Wi-Fi 6E standard, which extends the capabilities of traditional Wi-Fi networks into the 6 GHz frequency band. Wi-Fi 6E offers increased spectrum availability and reduced interference, enabling higher data rates and improved performance for wireless connectivity applications.

Wireless Gigabit connectivity has numerous applications across various industries, including consumer electronics, enterprise networking, automotive, and healthcare. With its high-speed, low-latency communication capabilities, wireless Gigabit connectivity is poised to revolutionize the way we connect and interact with devices, enabling new opportunities for innovation and productivity in the digital era.

6. Medical Imaging and Healthcare

MmWave technology is finding applications in medical imaging and healthcare, enabling non-invasive diagnostic imaging techniques and remote patient monitoring systems. MmWave imaging systems, such as mmWave scanners and sensors, provide high-resolution

imaging of internal tissues, organs, and physiological parameters, facilitating early detection and diagnosis of medical conditions. MmWave technology also supports wireless health monitoring devices and wearable sensors for continuous patient monitoring and telemedicine applications. Medical imaging plays a crucial role in modern healthcare by providing valuable insights into the structure, function, and health of the human body. These imaging techniques enable healthcare professionals to diagnose diseases, monitor treatment progress, and guide surgical interventions with precision and accuracy.

One of the most widely used medical imaging modalities is X-ray imaging, which uses ionizing radiation to create detailed images of bones, tissues, and organs. X-rays are commonly used to detect fractures, tumors, and abnormalities in the skeletal system and soft tissues. Another common imaging technique is computed tomography (CT) scanning, which combines X-ray images taken from multiple angles to create cross-sectional images of the body. CT scans are used to visualize internal organs, blood vessels, and soft tissues with high resolution, making them valuable for diagnosing conditions such as cancer, cardiovascular disease, and neurological disorders. Magnetic resonance imaging (MRI) uses powerful magnets and radio waves to generate detailed images of the body's internal structures, including the brain, spinal cord, and joints. MRI is particularly useful for imaging soft tissues and organs, as well as detecting abnormalities such as tumors, inflammation, and injury.

Ultrasound imaging utilizes high-frequency sound waves to produce real-time images of the body's internal organs and structures. Ultrasound is non-invasive, safe, and versatile, making it suitable for a wide range of applications, including prenatal care, cardiovascular imaging, and diagnostic procedures as in Fig. 9.

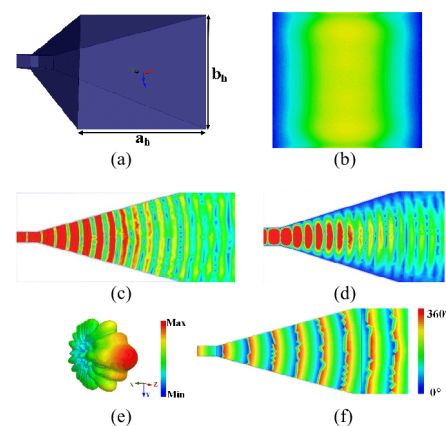


Fig. 9: The geometry of the classic airhorn

In addition to these traditional imaging modalities, emerging technologies such as positron emission tomography (PET), single-photon emission computed tomography (SPECT), and molecular imaging are advancing the field of medical imaging, enabling earlier detection, more accurate diagnosis, and personalized treatment planning for patients.

7. Aerospace and Defense

MmWave technology is utilized in aerospace and defense applications for radar systems, communication links, and electronic warfare (EW) systems. MmWave radar systems provide long-range detection and tracking capabilities for aircraft, ships, and ground vehicles, enabling surveillance, reconnaissance, and threat detection in military and security applications. MmWave communication links support high-bandwidth data transmission for military command and control systems, satellite communication terminals, and unmanned aerial vehicles (UAVs). Aerospace and defense industries are vital sectors that encompass a wide range of activities related to aviation, space exploration, and national security. These industries play a crucial role in shaping the global economy, advancing technological innovation, and ensuring the safety and security of nations worldwide.

In the aerospace sector, companies design, manufacture, and maintain aircraft, helicopters, unmanned aerial vehicles (UAVs), and spacecraft for civilian and military applications. Aerospace technology enables air transportation, satellite communications, weather forecasting, and earth observation, facilitating global connectivity and improving quality of life. Additionally, advancements in aerospace engineering drive innovation in materials, propulsion systems, avionics, and aerodynamics, leading to more efficient, sustainable, and safer air travel. The defense industry focuses on developing and producing military equipment, weapons systems, and defense technologies to safeguard national interests and protect against external threats. Defense technologies encompass a wide range of capabilities, including missile defense systems, electronic warfare, surveillance and reconnaissance, cyber defense, and unmanned combat systems. These technologies are essential for maintaining military readiness, deterring aggression, and ensuring the security of borders and critical infrastructure.

Overall, the aerospace and defense industries are at the forefront of innovation and technological advancement, driving economic growth, scientific discovery, and national security priorities around the world. Continued investment in research, development, and collaboration

within these sectors is essential for addressing emerging threats, enhancing global security, and exploring new frontiers in space exploration.

8. Industrial Automation and IoT

MmWave technology is driving innovation in industrial automation and the Internet of Things (IoT), enabling wireless sensor networks, industrial robotics, and smart manufacturing systems. MmWave sensors and communication modules provide real-time monitoring and control of industrial processes, equipment, and assets, optimizing efficiency, productivity, and safety in manufacturing facilities, warehouses, and industrial environments. Industrial automation and the Internet of Things (IoT) are revolutionizing the manufacturing sector, driving efficiency, productivity, and innovation across industries. Industrial automation involves the use of advanced technologies such as robotics, sensors, and control systems to automate manufacturing processes and operations. By integrating automation technologies with IoT connectivity, manufacturers can create smart, interconnected systems that optimize production, reduce costs, and improve quality.

IoT-enabled industrial automation systems leverage sensors and data analytics to collect real-time information from equipment, machines, and production lines. This data is then analyzed to identify inefficiencies, predict maintenance needs, and optimize production schedules in real-time. By providing insights into equipment performance, energy consumption, and supply chain management, IoT-enabled automation systems enable manufacturers to make informed decisions and achieve operational excellence as in Fig. 10.

Key applications of industrial automation and IoT in manufacturing include predictive maintenance, remote

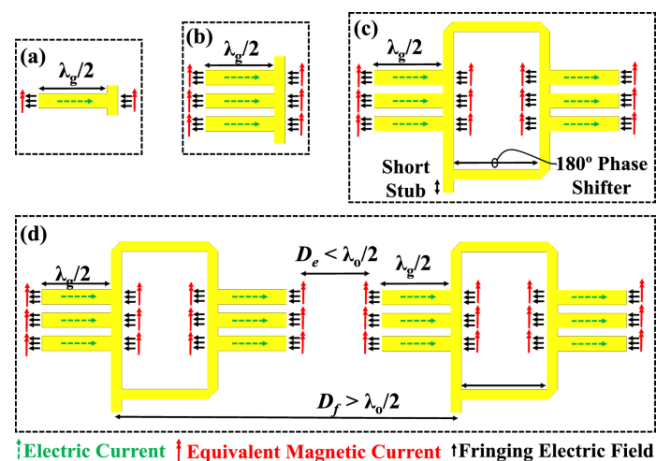


Fig. 10: Millimeter-wave planar antenna array

monitoring and diagnostics, asset tracking, and smart logistics. These technologies enable manufacturers to streamline production processes, reduce downtime, and enhance product quality, ultimately driving competitiveness and profitability in a global marketplace.

As industrial automation and IoT continue to evolve, manufacturers are exploring new opportunities to leverage emerging technologies such as artificial intelligence (AI), machine learning, and augmented reality (AR) to further enhance productivity, flexibility, and agility in manufacturing operations. By embracing digital transformation and investing in advanced automation solutions, manufacturers can unlock new levels of efficiency and innovation to meet the demands of a rapidly changing market landscape.

INNOVATIONS AND FUTURE DIRECTIONS

As mmWave technology continues to evolve, new innovations and advancements are on the horizon, unlocking even greater potential and expanding the boundaries of what is possible. Some areas of future development and innovation include:

- **Beamforming and MIMO Techniques:** Advancements in beamforming and multiple-input multiple-output (MIMO) techniques will enhance the performance and reliability of mmWave communication systems, enabling robust connectivity in challenging environments and urban areas.
- **Integration with Satellite Communication:** MmWave technology may be integrated with satellite communication systems to extend broadband connectivity to remote and underserved regions, enabling global access to high-speed internet and digital services.
- **IoT and Smart Cities:** MmWave technology will play a crucial role in enabling smart cities and IoT deployments, providing connectivity for a wide range of smart devices, sensors, and infrastructure. MmWave networks will support applications such as smart transportation, environmental monitoring, and energy management, contributing to the development of sustainable and resilient urban ecosystems.
- **Healthcare and Telemedicine:** MmWave technology will enable new applications and services in healthcare and telemedicine, supporting remote patient monitoring, teleconsultation, and medical diagnostics. MmWave-enabled medical devices and wearables will provide real-time health monitoring

and personalized healthcare services, improving patient outcomes and healthcare delivery.

- **Edge Computing and Cloud Services:** MmWave technology will facilitate the deployment of edge computing and cloud services at the network edge, enabling low-latency data processing and real-time analytics for mission-critical applications. MmWave-enabled edge computing platforms will support applications such as autonomous vehicles, industrial automation, and immersive multimedia experiences, enhancing performance and responsiveness.
- **Environmental Sensing and Remote Sensing:** MmWave technology will enable new applications in environmental sensing and remote sensing, supporting climate monitoring, weather forecasting, and natural disaster management. MmWave sensors and satellite systems will provide high-resolution data on atmospheric conditions, oceanography, and land cover, facilitating scientific research and environmental conservation efforts.

CONCLUSION

In conclusion, millimeter-wave technology represents a transformative force in wireless communication, enabling a wide range of applications across industries and sectors. From 5G wireless networks and automotive radar to medical imaging and industrial automation, mmWave technology is driving innovation, transforming industries, and shaping the future of connectivity. As we continue to explore the boundless potential of mmWave technology, new opportunities and possibilities will emerge, ushering in a new era of connectivity, collaboration, and innovation.

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