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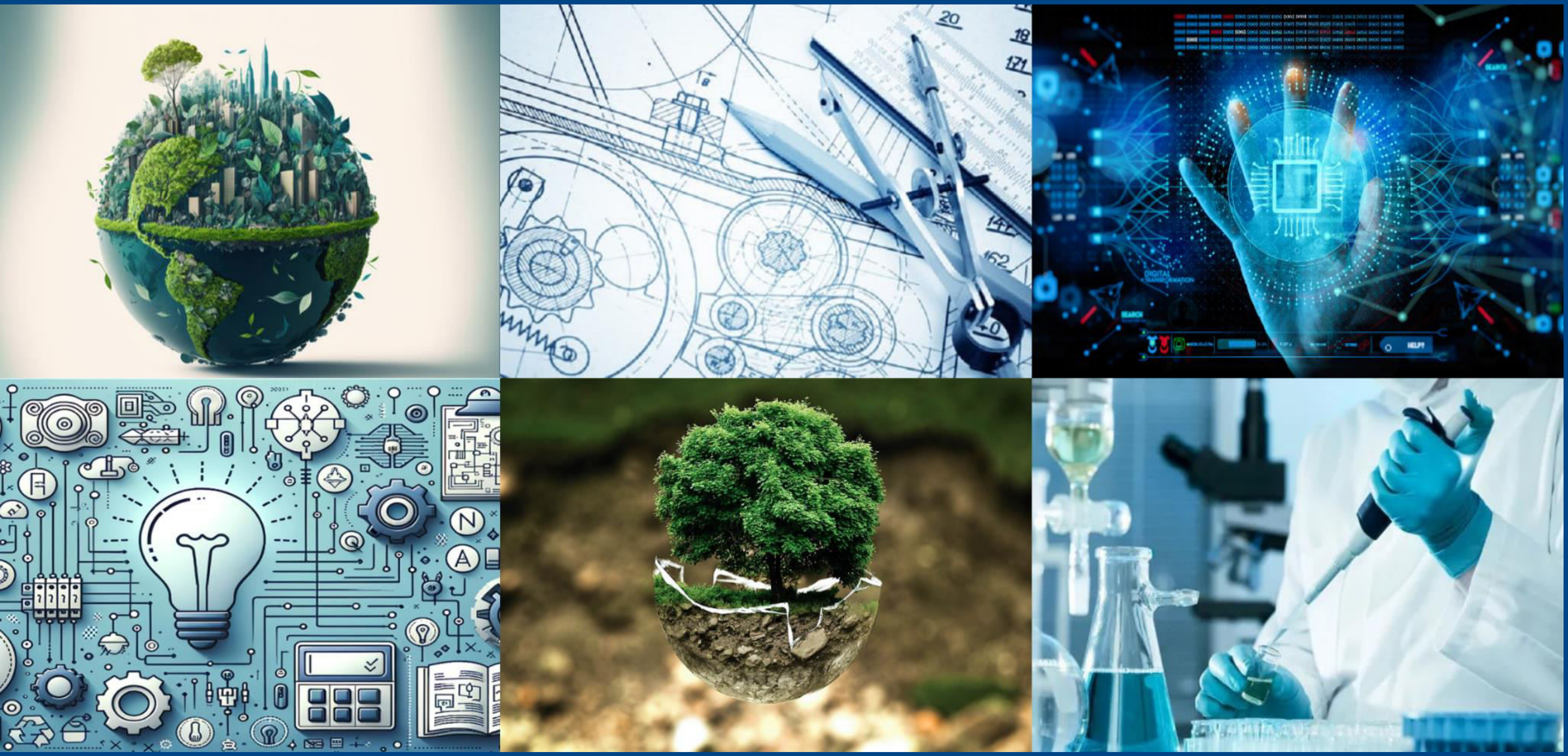

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AI-Driven Wearable Metamaterial Sensor for Non-Invasive Continuous Health Monitoring

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ABSTRACT: AI-has revolutionized the field of wearable sensors in remote health monitoring gives real time data and alert signal for real time diagonist and personalized anticipatory disease management. This review brings together the latest breakthroughs in AI-powered biosensor technologies, showcasing their expanding role in managing diverse health conditions—from diabetes and cardiovascular diseases to neurodegenerative disorders, mental health, and maternal and neonatal care—while addressing key concerns surrounding scalability, privacy, and system resilience

There are advancved machine learning methods using multi layer neural network to learn complex neural patterns automatically from large real time data set used in CNN,RNN,LSTM,transformers through image analysis and signal processing through biomedical sensing which are useful for biomedical sensors made up from metamaterial.By going through literature review the key features highlights preventive real time health monitoring system based on IoT sensors

Such as continuous glucose monitoring,cardiovascular,CKD highlights.The accuracy and efficiency of the wearable devices in processing the psychological signals arise from the autisim signals are tested and the device configuration can be optimized accordingly.

Although wearable healthcare technologies have advanced rapidly, critical challenges remain, including variability among sensing platforms, increasing concerns over data confidentiality, and the limited ability of existing models to generalize across diverse user populations. Recent developments in machine learning, such as convolutional and recurrent neural networks, ensemble-based classifiers, federated learning systems, and large language models for clinical context analysis, are reshaping intelligent biosensing applications and improving the reliability of real-time health assessment. Moreover, the integration of explainable and counterfactual learning strategies is strengthening interpretability and fostering greater confidence in automated diagnostic systems Parkinson's disease is a long-term neurological disorder that progressively impairs movement, cognition, and daily functioning. Recent innovations in wearable sensing devices, combined with intelligent machine learning algorithms, allow continuous and non-invasive monitoring of key symptoms such as tremor intensity, gait instability, and speech alterations. These data-driven approaches provide reliable indicators for early-stage identification and personalized tracking of disease progression.Refined

KEYWORDS: Digital twin; Counterfactual explanation; Wearable biosensors; Personalized health monitoring; Large language models (LLMs); Hydration sensing; Continuous glucose monitoring; Stress detection; Behavioral health; Deep learning; Human-in-the-loop systems; Real-time monitoring; Parkinson's disease; Gait analys

I. INTRODUCTION

The integration of wearable biosensors, artificial intelligence (AI), and wireless communication technologies has revolutionized remote health monitoring by enabling continuous, non-invasive acquisition and intelligent interpretation of physiological signals. Wearable sensing devices can continuously monitor parameters such as heart rate, glucose levels, gait patterns, hydration status, and electrocardiogram (ECG) signals, thereby facilitating real-time diagnostics and personalized healthcare interventions. This shift from episodic clinical measurements to continuous monitoring supports proactive disease management and precision medicine frameworks [1], [2].

Recent advancements in flexible electronics, low-power circuits, and wireless body area networks (WBANs) have accelerated the development of smart wearable health monitoring systems capable of functioning in both clinical and home environments. These systems play a critical role in managing chronic diseases such as diabetes, cardiovascular disorders, and neurodegenerative conditions by enabling early detection of physiological abnormalities and timely clinical response [3], [4]. Furthermore, the emergence of continuous glucose monitoring (CGM) devices and intelligent health patches demonstrates the growing importance of wearable biosensors in patient-centric healthcare ecosystems [5].

Artificial intelligence has significantly enhanced the analytical capabilities of wearable sensors by enabling automated extraction of clinically relevant biomarkers from complex physiological data streams. Machine learning and deep learning techniques—including convolutional neural networks (CNNs), recurrent neural networks (RNNs), and long short-term memory (LSTM) models—have shown high accuracy in analyzing multimodal biosignals such as heart rate variability, gait dynamics, and electrodermal activity [6], [7]. More recently, federated learning, transfer learning, and edge-AI architectures have been introduced to address privacy, latency, and scalability challenges by enabling decentralized and device processing of health data [8].

In parallel, metamaterial-based electromagnetic structures have revolutionized the next generation AI dependent biosensors which are dependent on microwave and optical metamaterials having properties such as negative permittivity, strong electromagnetic field confinement, and tunable resonance characteristics. These features enable highly sensitive detection of small dielectric variations in biological tissues, which can be correlated with physiological changes such as glucose concentration, hydration level, and tissue composition [9]. Consequently, metamaterial-inspired wearable sensors and antennas are increasingly being explored for non-invasive biomedical sensing and wireless health monitoring applications, particularly in 5G-enabled telemedicine systems [10].

Due to the vast expansion of wireless communication, the necessity of high frequency spectrum is in greater demand [11]. The improvement of modern wireless technologies including Wi-Fi 5, Wi-Fi 6, 4G LTE and 5G have presented better innovations and merits over the industry [12]. The present 4G LTE communication in case of smart appliances generate a moderate data rate and capacity that influences from spectrum limitation. The 5G technology is an advanced form of 4G LTE with rapid connections, additional capacity and increased throughput [13]. For a better outcome, the 5G communication system needs higher data rate, larger bandwidth and wider capacity.

Nowadays, the 5G technology are highly affected due spectrum shortage problems [14]. The major requirement for the 5G application is to provide sub-6 frequency of range 2-5GHz and for manipulating above 6GHz, the frequency range must be compatible to provide 24-71GHz [15]. Normally, the mm wave have the frequency range of 30-300GHz and it is integrated with 5G applications capable of handling above 6GHz frequency range [16]. To comply diverse necessities of 5G technology, an efficient antenna with huge bandwidth, steady radiation pattern and enhanced gain are needed [17]. The researchers have designed diverse antenna types including monopole antenna, patch antennas, dipole antennas, loop and antipodal Vivaldi antenna (AVA) in case of 5G applications [18].

From these types, AVA can be utilized for larger frequency spectrum and shows outstanding performance especially in mm wave 5G applications [19]. The AVA is invented by Dr. Gibson and later it is changed into antipodal shape for improving the directivity, gain and bandwidth of the Vivaldi antenna [20]. The AVA consist of several parameters like antenna length, width, tapered length, rate, slot line length, back wall offset (BWO) and opening mouth (OM) that plays an important role in minimizing the bandwidth consumption and refection coefficient [21]. Due to increased band spectrum, the parameters of the AVA gets affected. For improving the parameters of the AVA, dielectric lens, parasitic patch, balanced AVA, metamaterial, array and MIMO are utilized [22]. In this, the dielectric lens is one of the material that can be utilized instead of substrate having varying relative permittivity. But it highly depends upon the antenna size and is cost effective [23].

In existing studies [24], utilized elliptical shape parasitic patch for increasing the bandwidth and gain of the antenna. However, this material suffers from high hardware complexity. For the balanced AVA (B-AVA), three basic layers are present namely double ground patches and single patch radiators that acts as a sandwich between patch grounds [25]. The B-AVA can produce a cross view beamforming but it is complex structure. Recent studies [26] utilizes array antenna for maximizing the diversity gain and avoids the antenna to take multi-path fading. Several researchers have investigates the different antenna performance for enhancing the communication performance [27]. In [18], 1×4 array AVA used with substrate integrated waveguide (SIW) and that prodfucves the gain of 23dBi. However, the determination of dimension and position of the antenna remains the complex task [28]. To overcome this issue, slots are integrate at the ground plane that can normalize meander lines (ML) between different micro-strip patch antennas

[29]. There are different slot shapes for reducing the MC between the each antenna namely circular, rectangular, H-shaped, U-shaped, L-shaped slot etc. [30]. Antenna PCB surface area can be reduced using corrugation and it may be triangular, rectangular or square shape etc. Most of the existing works utilizes rectangular corrugations of maximizing the antenna efficiency [31]. In addition to the slots and metamaterial, defected ground structure and asymmetrical co-planar strip wall also play an integral role in reducing the MC between the antenna elements. Moreover, electromagnetic band-gap (EBG) and split-ring resonator (SRR) structures are inserted between two antennas to improve the MC. Utilization of EBG in the feeding network for eliminating the wave surfaces and MC in the antenna [32].

Recently, the metamaterial play an vital parameter in reducing the size of the antenna and have the capability to produce multi-band frequencies effectively. There are many different kinds of metamaterial are present that provides varying permittivity based on its nature [33]. The metamaterial having negative permittivity then it is said to be epsilon negative (ENG) permittivity [34] and if the relative permittivity is negative then it is considered as the mu negative permittivity (MNG) [35] and if both are negative then it is double negative (DNG) [36] permittivity. Based on their behaviour, the metamaterial are separated into different types as anisotropic, photonic, isotropic, chiral, and frequency selective-surface . The metamaterial have numerous advantages like increasing bandwidth, reduces MC and improves gain effectively [. Traditional AVA, the antenna is contemplated between double metamaterial slabs for maximizing the directivity and for generating fixed radiation performance. The conventional meander-line, W-shaped metamaterial structure can provide enhanced half power beam-width especially in 5G applications [30].

Some of the recent works done by different authors:

Amruta S. Dixit & Sumit Kumar [31] suggested antipodal vivaldi antenna (AVA) using metamaterial for enhancing gain in 5G applications. The dimensions of the suggested AVA were $24mm \times 50mm \times 1mm$. The property of negative relative permittivity was exhibited by ‘V’ meta-material and so it was called epsilon negative metamaterial (ENG). To transmit more energy in end-fire direction, the ENG unit cells were organized in between the two AVA flares. The gain of the antenna differs between 10.9 and 13.82 dBi in 24-30 GHz frequency range, which made it appropriate for 5G applications.

Amruta S. Dixit & Sumit Kumar [32] introduced a low profile AVA with substantial enhancement in front-to-back ratio as well as sidelobe levels (SLL) in order to tackle adverse effect in 5G communication system. This AVA had modelled by integrating corrugations and substrate integrated waveguide (SIW) for 38 GHz band of communication system and it comprised of 36 to 48.43 GHz of impedance bandwidth. Besides, the antenna efficiency was above 94% over the desired range of frequency and the usage of SIW enhanced SLL and bandwidth.

Amruta S. Dixit & Sumit Kumar [33] described AVA based on fermi-dirac function for millimeter wave (mmWave) application to accomplish broadband performances. This model had offered an outstanding fractional bandwidth, which ranges between 10.45 and 300 GHz. The outer exponential curve was initially modelled by fermi-dirac function whereas, the inner curve was quarter part of circle. Besides, the rectangular shaped corrugations improvement scheme was integrated in AVA in order to improve gain and bandwidth.

Innocent Kadaleka Phiri & Kumaresh Sarmah [34] presented AVA array with enhanced ground plane as well as slotted radiators for 5G mmWave applications. In the beginning, single element AVA was modelled, and further an array with elements of 4×1 AVA and a 3dB power divider was modelled on $28 \times 32 \times 1.6mm^3$. The operating bandwidth of array antenna was improved by the addition of cuts. On the feeding section, the structural enhancement of ground plane enhanced array antenna gain, operating bandwidth, and impedance matching.

II. METHODOLOGY AND DESIGN

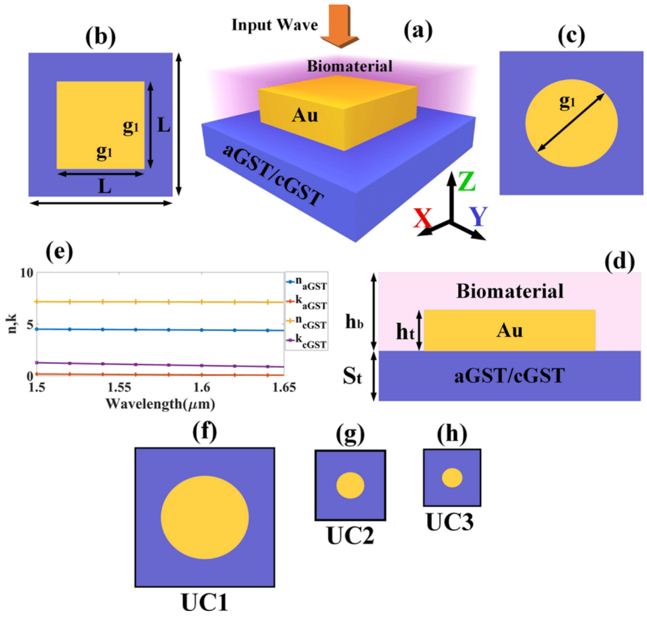
Despite these technological advances, several challenges remain in the large-scale deployment of AI-powered wearable health monitoring systems. Sensor heterogeneity, motion artifacts, and inter-subject variability can reduce measurement reliability, while issues related to data privacy, cybersecurity, and interpretability of AI models hinder clinical adoption. Addressing these challenges requires robust multimodal sensing architectures, explainable AI frameworks, and standardized validation protocols to ensure reliable and equitable healthcare delivery across diverse populations .

In this context, the present work reviews the state-of-the-art developments in AI-powered wearable biosensors for non-invasive continuous health monitoring, with a particular emphasis on metamaterial-enabled sensing technologies. By bridging advances in biosensing hardware, AI-driven analytics, and wireless healthcare communication, this review highlights current progress, identifies research gaps, and outlines future directions for scalable, privacy-preserving, and clinically reliable intelligent wearable healthcare systems.

The proposed MM based biosensor is used for detection of hemoglobin and urine using phase change material; enables tunable optical sensing.

Biosensor composition: Structure made of phase-change material; specifically Ge2Sb2Te5 (GST) with alloy combinations. GST changes phase with temperature, enabling tunable sensing for biosensing applications. Biosensor Design: Structures incorporate cubical/cylindrical gold resonators placed on top of GST substrate. GST used as the base material, leveraging its phase-change property (aGST ↔ cGST).▪ Dimensions of the structure are:

St = 800 nm, ht = 600 nm, hb = 2000 nm, g1 = 1400 nm, and L = 2000 nm.



Unit Cell Configurations:

- Biosensor includes three different unit cell designs (UC1, UC2, UC3).

➢ UC1: L × L = 2000 × 2000 nm2 with g1= 1400 nm
➢ UC2: L × L = 666 × 666 nm2 with g1= 466 nm
➢ UC3: L × L = 400 × 400 nm2 with g1= 280 nm

Each has a different size, which affects the sensor's tunability.
Sensing Mechanism: The sensor detects changes in the refractive index of an analytic (e.g., hemoglobin or urine) by measuring the shift in its absorption peaks.
Tunability: Phase transition of GST (from amorphous to crystalline) allows spectral response to be tuned. Also; the number of resonators in an array provides tunability for both aGST and cGST-based biosensors.
Optical Behaviour: Absorption (A): $A = 1 - T - R$

III.IMPEDANCE MATCHING THEORY

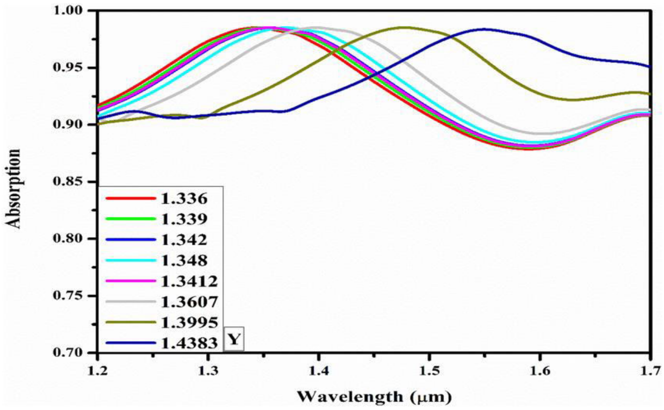
For maximum absorption: reflection (R) → 0; when impedance of free space and device is matched. For this case; overall transmission will be reduced from T = e−2n2dk to T = e−αd; where k is the free space propagation vector, d is the thickness of sample, n2 is the effective refractive index. Transmission (T) decreases exponentially with thickness and absorption coefficient (α). The value of effective refractive index (n2) is determined by the refractive index of the spacer material (GST in this case).

Therefore; achieving large effective refractive index (n2) enhances absorption efficiency. To achieve near-unity absorption, n2 must be as large as possible.Tunable Infrared Metamaterial-based Biosensor
▪ Sensor testing:
- Built using amorphous GST (aGST) and crystalline GST (cGST) in different structural designs.
- Tested with varying biomolecule concentrations:
  ➢ Hemoglobin: 10 g/L, 20 g/L, 30 g/L, 40 g/L.
  ➢ Urine: 0–1.5 mg/dL, 2.5 mg/dL, 5 mg/dL, 10 mg/dL.

aGST (Amorphous) Substrate: Typically shows a sharper resonance peak with a lower absorption amplitude compared to cGST.
cGST (Crystalline) Substrate: Exhibits higher absorption (near-perfect absorption) due to the higher dielectric constant, making it more sensitive to small changes in biomolecule refractive indices.

Resonator Shapes: Both cubic and cylindrical resonators on GST act as plasmonic sensors, with the absorption spectrum shifting based on the dielectric environment.

Key Findings: The sensor shows linear sensitivity, with the wavelength shifting by several nanometers for different, small changes in the refractive index, useful for detecting glucose or hemoglobin level.



Properties of Metamaterial

The interaction of these materials with the electromagnetic waves is governed by the frequency (f) dependent material properties such as permittivity, ε(f), and permeability, μ(f).
▪ All the naturally occurring materials have positive permeability, μ f and positive/negative permittivity, ε f , and, which govern the electromagnetic responses of these materials.
▪ However, for various modern technological advancements in communication, imaging, and sensing, engineers need precise control over the behavior of electromagnetic waves interacting with these materials to achieve specific functionalities.
▪ Metallic, semiconductor, and insulating structures can be designed as 'meta-atoms' or 'building blocks' to construct metamaterials.

- Provide tailored/artificial material properties such as negative permittivity ε(f) and/or permeability μ (f)over a specific electromagnetic band. Metamaterials show electromagnetic properties not depending on their raw material composition but from assembly of sub-wavelength sized individual elements i.e. meta-atoms

A. Fundamentals of Metamaterial Absorbers

The first demonstration of a "perfect" metamaterial absorber was reported by Landy et al., achieving near-unity absorption at microwave frequencies via a resonant electric–magnetic response [11]. Following this, Watts et al. provided a comprehensive review of metamaterial absorber physics and early designs, laying the groundwork for broadband and polarization-insensitive structures [12].

B. Broadband & Angular-Stable Designs

To meet the wide bandwidth requirements of 5G, Cui et al. engineered a broadband absorber using nested sub-wavelength resonators, demonstrating >90% absorption over a 2:1 bandwidth and angular stability up to 60° incidence [13]. Chen et al. subsequently reviewed metasurface techniques for wide-angle operation, highlighting strategies to maintain high absorption under oblique polarization [14].

C. EMI Suppression in 5G Devices

Tao et al. applied metamaterial absorbers directly to EMI shielding, designing a dual band structure that suppressed spurious radiation in both sub-6 GHz and X-band, with measured S_{11} below –15 dB [5]. Zhao et al. focused on 3.5 GHz (a key 5G band), embedding absorbers into smartphone PCB stacks and demonstrating a 12 dB reduction in mutual coupling between antenna elements [6].

D. Conformal & Wearable Absorbers

For flexible electronics, Smith and Jones developed a polymer based metamaterial sheet that conformed to curved surfaces, achieving >85% absorption across 24–30 GHz and maintaining performance under 5 mm bending radius—critical for wearable 5G modules [7].

E. Reconfigurable & Integrated Solutions

More recent work by Tsakmakidis et al. introduced tunable absorbers using varactor-loaded resonators, enabling dynamic adaptation to shifting EMI spectra in 5G transceivers. Their prototype demonstrated real-time tuning over a 5 GHz span with minimal insertion loss [8].

Metamaterial absorber Structure Design

Top Layer: Resonator Pattern(Split Ring,Square Patch,Jeruselem cross)
Middle Layer:Substrate(FR4,Roger R03003,Taconic)
BottomLayer:GroundPlane(Copper)

Design Parameter for(3.5GHz,wavelength 85.7 mm Absorpant)

Substrate Parameter

Parameter	Description
Material	Common Choice FR4,Rogers RT 5880,Taconic flexible PETs
Dielectric Constant (εr)	2.2-4.4
Loss Tangent (tanδ)	Should be low for efficient absorption
Thickness	Usually between 0.2 -1.6 mm

Unit Cell Dimension

Parameter	Description
Periodic unit cell size	Size of the repeating unit 5mmx5mm
Resonator Size(L,W)	Size of the inner resonating element typically 60-90% of unit cell size

Gap between resonator arms or lines usulally	0.2-1 mm
Metalayer Thickness	Usually17-35 µm (standard copper cladding)

Resonator Geometry

Type	Description
Jeruselem cross	Cross shaped with notched edges,effective
SRRs	Commonly used for narrowband or multiband design
Square/rectangular Loops	For simple ,symmetric absorption
Electric -LC	Compact and effective for lower frequencies
Fractal or Meanders Line	For miniaturization and multiband response

Ground plane Geometry

Parameter	Description
Material	Usually a continous copper layer
Thickness	Same as the top layer(17-35 µm)
Role	Prevent transmissions(ensures only absorption and reflection)

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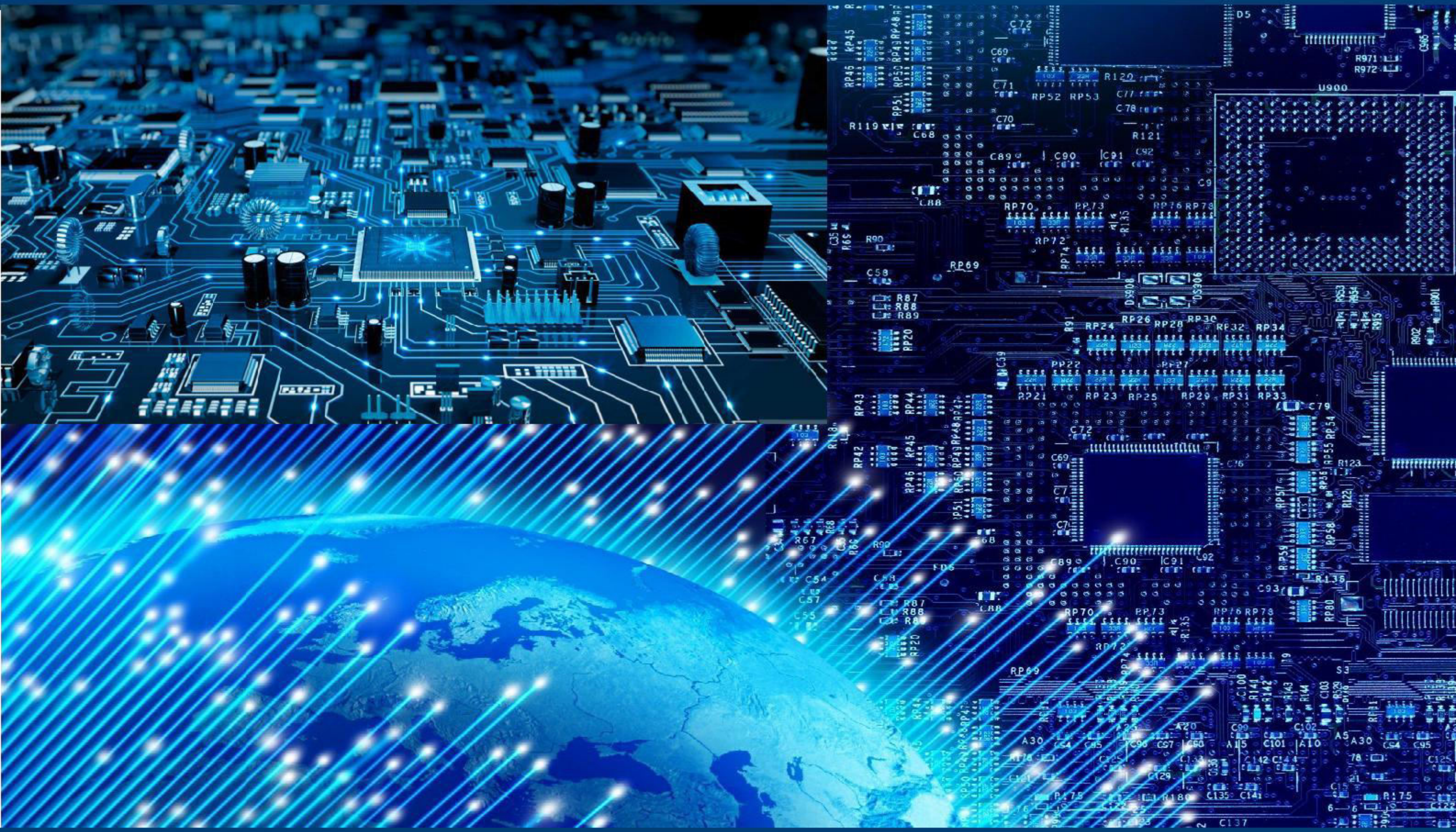

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