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Design and Performance Optimization of 2.4ghz Microstrip Patch Antenna for WI-FI, Wlan and Bluetooth Applications

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Abstract- The rapid expansion of the wireless communication systems has led to an immediate need for small antennas that can provide high performance and reliable operation in the 2.4GHz ISM band which is commonly used in Wi-Fi WLAN and Bluetooth systems. Microstrip patch antennas represent the optimal solution because they deliver compact design advantages and lightweight features and simplified manufacturing processes and printed circuit board compatibility. Conventional antennas however operate with restricted bandwidths which create impedance matching issues that degrade their overall transmission capacity. The study investigates the creation and improvement process of 2.4Ghz microstrip patch antenna through the application of an FR4 substrate and microstrip line feeding system. The key parameters such as patch length, patch width are optimized to enhance bandwidth and overall antenna performance. The simulation results shows that return loss has decreased to a value below -10db and VSWR reaches an acceptable level below 2 while gain operates at the needed resonant frequency. The developed design is suitable for wireless communication devices including Wi-Fi routers, Bluetooth modules and WLAN enabled systems which provide both dependable short-range communication and overall stability.

Keywords— Antenna design, Bluetooth, Electromagnetic simulation, HFSS, ISM band, Microstrip antenna, Performance optimization, Return loss, Wireless communication, Wi-Fi, WLAN

I. INTRODUCTION

Wireless communication systems continue to evolve rapidly, increasing the need for compact and efficient antennas operating in the 2.4 GHz ISM (Industrial, Scientific, and Medical) band. This frequency range is broadly used by Wi-Fi, WLAN, and Bluetooth technologies, which are integrated into modern devices such as routers, smartphones, wearable electronics, and IoT modules. These applications need antennas that provide stable radiation performance, accurate impedance matching, compact size, low fabrication cost and easily integrated with printed circuit board (PCB) technology [1], [5], [11].

Microstrip patch antennas are well adapted for such applications due to their low profile, lightweight structure, and ease of fabrication using standard PCB processes. The antenna performance primarily depends on patch dimensions, feeding technique, and substrate properties, which determine important parameters like return loss, resonant frequency, gain, and bandwidth [2], [3]. Despite their advantages, conventional microstrip patch antennas commonly face narrow bandwidth and moderate gain, making optimization necessary for reliable wireless operation [3], [10].

Several studies have focused on improving 2.4 GHz antenna performance through precise dimensional tuning, optimized feed positioning, and structural modifications that extend the effective current path [4]– [6], [10], [13]. Other approaches include parametric analysis, array configurations, and advanced optimization techniques such as simulation-driven and machine learning-based methods [8], [9], [12]. However, achieving exact resonance at 2.4 GHz on low-cost substrates remains challenging, as small dimensional variations can result in frequency shifts and increased reflection losses [4], [11].

In this work, a microstrip patch antenna is designed, simulated, and optimized using the ANSYS HFSS to achieve precise resonance at 2.4 GHz with low return loss, acceptable VSWR, and stable radiation characteristics. The antenna dimensions are precisely refined to enhance impedance matching while maintaining satisfactory structural simplicity. The developed design offers a compact and effective solution for integration into Wi-Fi, WLAN, and Bluetooth communication systems operating in the ISM band.

II. LITERATURE REVIEW

The compact design of microstrip patch antennas which exact at 2.4 GHz makes them ideal for use in wireless communication devices such as Wi-Fi and WLAN and Bluetooth and IoT systems because they can be made using standard PCB manufacturing methods C.A. Balanis [2] provided an explanation of microstrip antenna theory which shows how the design of antennas together with their substrate elements and their feed systems all determine their resonant frequencies and radiation properties. K. P. Ray and G. Kumar[3] explain that conventional rectangular patches show narrow bandwidth characteristics because their high-quality factor limits their signal transmission capacity.

The research team proposed structural changes to achieve better impedance matching together with increased bandwidth performance. P. Vetriselvi, S. Murugan, and V. Rajamani [10] proved that the integration of slots increases bandwidth because it changes how surface currents flow through the material. S. Gao et al. [1] created a small antenna which operates in Wi-Fi frequency ranges while M. F. Zambak et al. [4] suggested an L-shaped patch design which serves IoT application needs. The designs achieve smaller dimensions compared to other existing design but they still limit bandwidth and gain performance.

A. Arora et al. [5] and M. P. Joshi and V. J. Gond [6] demonstrated that precise dimension control together with accurate feed positioning methods is essential for achieving 2.4 GHz resonance. M. S. Rana et al. [7] showed that even minor size changes can affect resonant frequency because it depends on FR-4 substrate material dimensions.

The work completed by A. ElAbbasi [8] and A. Mersani [9] and his team in their study used machine learning and parametric simulation optimization method to improve antenna design parameters. The methods achieve their purpose yet they create extra difficulties for computational work. B. Sai Sandeep and S. S. Kashyap [12] researched gain enhancement through array systems which required bigger equipment. The research studied dual-band systems and newly developed nano-antenna designs which S. Kumaravel et al. [13] and K. S. Shinde et al. [14] discovered yet their actual use remains difficult to achieve.

The design process faces its main obstacle because engineers need to build 2.4 GHz resonance systems that deliver necessary bandwidth while maintaining steady impedance matching on inexpensive substrates.

III. DESIGN METHODOLOGY

The presented antenna is designed for a rectangular microstrip patch antenna which is operating at 2.4GHz ISM Band. The design methodology consists of substrate selection, dimension calculation, feeding technique, systematic parametric optimization using simulation.

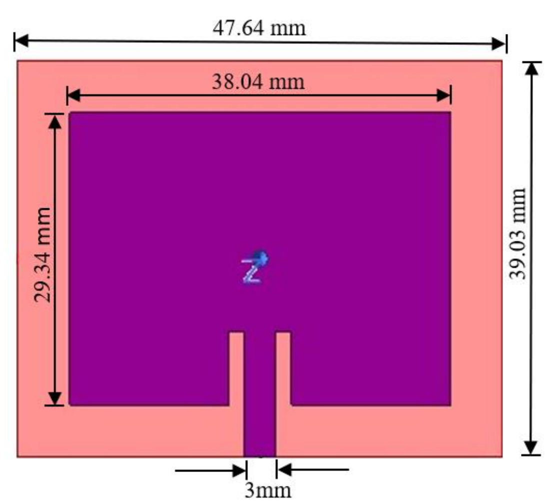


Fig-1 Antenna Dimension

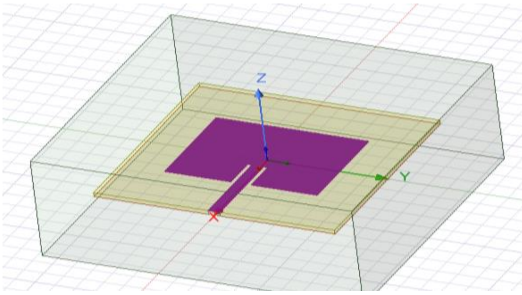
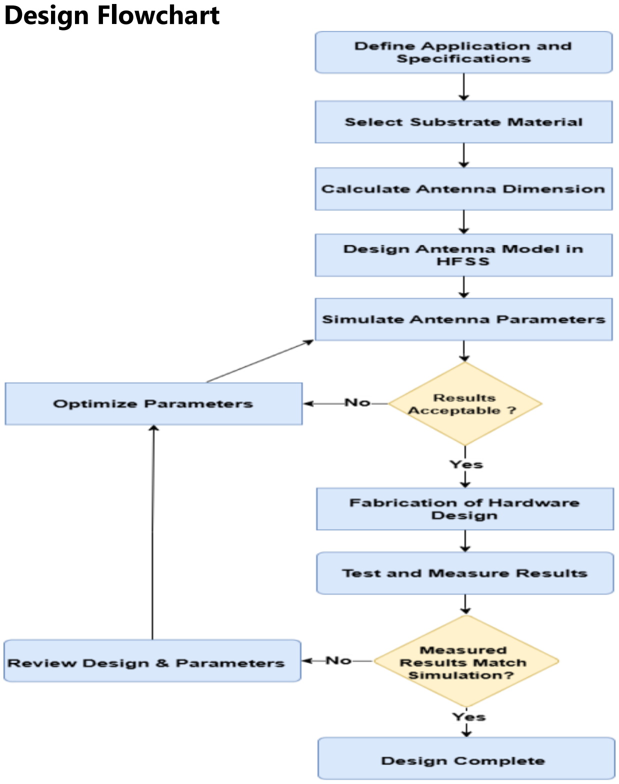


Fig-2 Microstrip patch antenna model

Design Flowchart



Selection of Substrate

FR-4 epoxy has a dielectric constant of ▪r = 4.4 and a thickness of h = 1.6mm and a loss tangent of 0.02. This provides a balance between the antenna size and the fabrication cost. Making use of high dielectric constant substrate results in smaller antenna dimensions but it also leads to decreased radiation efficiency while low dielectric substrate enhances performance yet results in higher production expenses according to references [2],[3]. Therefore, FR-4 is selected as an optimal solution for compact antenna and cost-effective for wireless communication systems working at 2.4GHz ISM band.

Calculation for Designing Antenna

Initial patch dimension are derived using the transmission line model approach to ensure resonance at desired frequency.

Data

Dielectric Constant ("ε" _"r") = 4.4

Frequency (fr) = 2.4 GHz = 2.4 x 〖10〗^9Hz

Height (h) = 1.6 x 〖10〗^(-3) m

Speed Of Light (Co) = 3 x 〖10〗^8 m/s

Calculations:

Step 1: Width of the Path (Wp):

$$Wp = \frac{c_0}{2f_r}\sqrt{\frac{2}{\varepsilon_r+1}} = \frac{3\times10^8}{2 \text{ X } 2.4\times10^9} \quad (1)$$

"Wp = 38.04 mm"

Step 2: Effective Dielectric Constant (εreff):

$$\varepsilon reff = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left(1+12x\frac{h}{Wp}\right)^{-\frac{1}{2}} \quad (2)$$

$$\varepsilon reff = \frac{4.4+1}{2} + \frac{4.4-1}{2}\left(1+12\times\frac{1.6}{38.04}\right)^{\frac{-1}{2}}$$

εreff= 4.09

Step 3: Effective Length (Leff):

$$\text{" } Leff = \frac{c}{2\times fr\times\varepsilon effc} = \frac{2}{2\times2.4\times10^{9}\sqrt{4.08}} \quad (3)$$

"Leff= 30.8mm"

Step 4: Length Extension (ΔL):

$$\Delta L = 0.412(\, h)\times\frac{\left(\frac{Wp}{h}+0.3\right)(\varepsilon reff+0.264)}{(\varepsilon reffc\text{-}0.258)\left(\frac{Wp}{h}+0.8\right)} \quad (4)$$

$$\Delta L = 0.412\ (1.6)\ \frac{(23.78+0.3)(4.087+0.264)}{(4.087+0.258)(23.78+0.8)}$$

"ΔL=0.734mm"

Step 5: Actual Length (Lp):

"Lp = Leff-2ΔL" (5)

"Lp = 30.8-2" ("0.734")=29.34 mm

Step 6: Ground Plane Dimensions:

Length of Ground (Lg)

$$Lg=6h+Lp=6(1.6)+29.43 \quad (6)$$

$Lg = 39.03$ mm

Width of Ground (Wg)

$$Wg=6h+Wp=6(1.6)+38.04 \quad (7)$$

$Wg = 47.64$ mm

Design Specification Of Proposed Antenna

TABLE I. Design Specification

Parameter	Value
Substrate Material	FR-4 Epoxy
Dielectric Constant (εr)	4.4
Substrate Height (h)	1.6 mm
Loss Tangent	0.02
Operating Frequency	2.4GHz
Patch Material	Copper
Ground Plane Material	Copper
Input Impedance	50 Ω

Feeding Technique Consideration

The researchers chose the microstrip line feed because it has a flat design that works with standard 50 Ω transmission lines. The microstrip feed system requires less effort to install because it maintains a complete planar design, which makes it simpler to use than coaxial probe feeding that needs vertical connections. The design of aperture-coupled and proximity-coupled feeds provides broader bandwidth capabilities but brings extra challenges for both design work and production processes. The microstrip feed serves as an effective solution for impedance matching because it enables simple matching procedures

Optimization Methodology

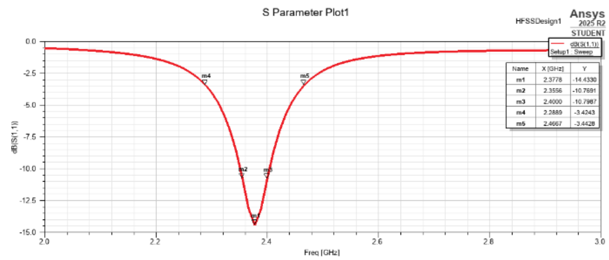
A parametric sweep analysis in the ANSYS HFSS optimizes the antenna by using finite element method electromagnetic simulation. The optimization process is structured.

The following parameters are systematically varied:
Patch Length (Lp) and Patch Width (Wp)
The system tests each parameter individually while monitoring S11, VSWR, and Resonant frequency.
The optimization process has these two goals:
Resonant frequency = 2.4GHz
Return Loss S11 <= -10dB
VSWR <= 2
This parametric optimization process enables frequency tunning and impedance matching while antenna maintains a compact design.

IV. RESULTS

Initial Simulation Results

Return Loss S11



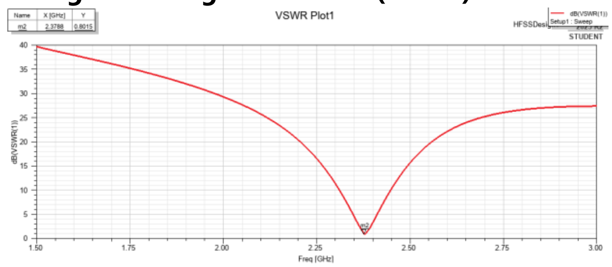
S11 Parameter

The simulated return loss from figure 3 shows that the antenna reaches its resonance point at 2.378GHz with a lowest return loss measurement of -14.43dB. This shows acceptable impedance matching since the return loss is below -10dB threshold. The system reflects less than 10% of incoming power while it radiates 90% of that power. The system needs further optimization because it produces a minor frequency shift from the expected resonant frequency. The system shows frequency shifts because of fringing effects and substrate losses and analytical calculation errors.

The -10dB bandwidth is observed nearly between 2.35GHz and 2.4GHz. Bandwidth= 2.400 -2.356, the resulting bandwidth equals 0.044 GHz = 44 MHz.

Voltage Standing Wave Ratio (VSWR)

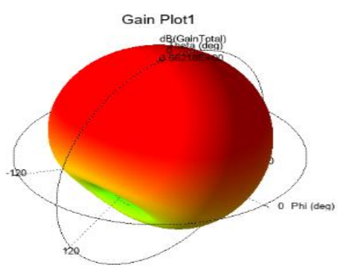
Voltage Standing Wave Ratio (VSWR)



VSWR Plot.

Figure4 displays that the minimum value of the VSWR plot reaches 0.8 at the frequency of 2.378GHz. The system demonstrates outstanding impedance matching capabilities when it operates at its resonant frequency. The feed line and antenna system achieve efficient power transfer because VSWR stays below 2.

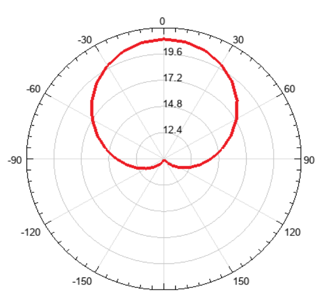
Gain



Gain Plot

The plot from Figure5 demonstrates that the maximum gain reaches approximately 3.56dB yet this value falls within the anticipated range. The antenna design appears in three-dimensional representation.

Elevation Radiation Pattern



Elevation Radiation Plot

The microstrip patch antenna projects its elevation radiation pattern through Figure 6. The system maintains consistent radiation output which results in a primary lobe that dominates all other radiation patterns. The radiation pattern displays a broad main lobe that extends toward the front side while it produces no radiation toward the back side thus showing its ability to radiate in a single direction. The antenna reaches its maximum gain of 14.8 dB when it operates at 2.4 GHz.

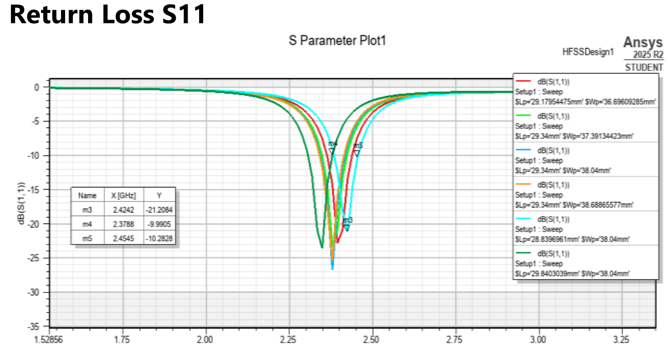
The initial design of the antenna displays fundamental operational capabilities yet it encounters numerous performance problems which affect its overall effectiveness:

The bandwidth of the antenna operates within a narrow range which measures approximately 44MHz. The current distribution of the system creates this restriction. The resonant frequency occurs at 2.378GHz instead of exactly 2.4GHz. The fringing effect together with dimension measurement errors from analytical work caused this issue. The bandwidth approximately 44MHz is relatively narrow. This limitation is due to its current distribution.

Optimized Antenna Performance

The parametric optimization through HFSS parametric sweep analysis to test various patch length and width combinations until found the desired 2.4GHz resonance peak was performed. The system enables precise adjustments for both electrical length and impedance attributes of the antenna system

Return Loss S11

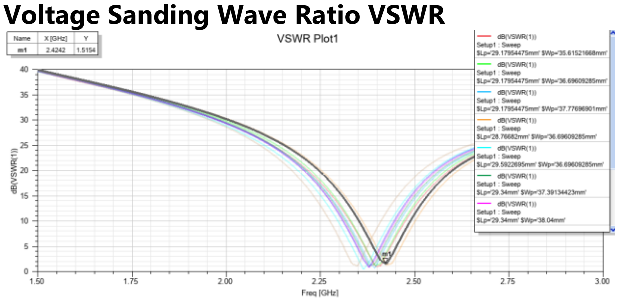


Optimized S11 Paramter Plot

The figure shows an S11 parameter optimization plot which displays its results. The optimized antenna shows a 2.424GHz resonance peak which reaches a minimum return loss of -21.21dB. The result shows better performance than the original design which had a minimum loss of -14.43dB at 2.378GHz. The frequency range between 2.40 and 2.45 GHz shows a strong resonance. The best result shown at the patch width (Wp)=38.04mm and length of patch (Lp)=28.83mm. The improved return loss test demonstrates outstanding impedance matching performance. A return loss below -20dB tells that only 1% power is reflected showing efficient power transfer.

The -10dB bandwidth shows its actual range between 2.3788 GHz and 2.4545 GHz. Bandwidth =2.4545-2.3788 = 0.0757GHz =75.7 MHz. The result demonstrates that optimization improved both impedance matching and frequency stability through better bandwidth performance.

Voltage Sanding Wave Ratio VSWR



Optimized VSWR Plot.

The optimized antenna from figure 8, shows a VSWR of 1.51 at 2.424GHz which meets acceptable standards because the VSWR value remains below 2. The system achieves effective impedance matching because it achieves optimal performance through its reflection control at operational frequency. The patch width (Wp) = 38.04mm and the patch length (Lp) = 28.83mm because the dimensions undergo optimization which results in VSWR measurements that approach 1. The measurement shows perfect alignment between the antenna system and its power supply system. The optimized curves show a VSWR measurement which stays under 2 during the operating frequency range, which demonstrates that power transfer occurs efficiently while signal reflection remains extremely low. The small shift in the VSWR dip among the curves shows how sensitive the antenna response is to changes in its dimensions. The microstrip patch antenna operates effectively at this time.

The frequency deviation after optimization is calculated as:

Frequency deviation = (2.424-2.4)/2.4 x100 = 0.83%

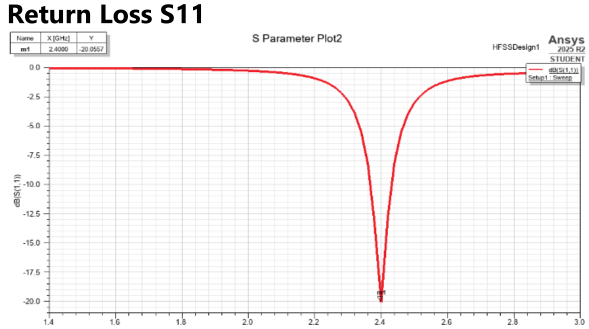
The antenna achieved its desired operating frequency through successful parametric optimization which produced only a minimal measurement deviation. The resonant frequency before optimization was 2.378 GHz.

The results of the parametric sweep show that patch length (Lp) determines resonant frequency while patch width (Wp) controls impedance matching and bandwidth. The resonant frequency decreases when patch length increases while it increases when patch length decreases. The patch length has been changed to 28.83mm from its previous value of 29.34mm which resulted in a change of the resonant frequency from 2.37GHz to 2.42GHz. The effective length of the antenna determines its resonant frequency through an inverse relationship.

Final Optimized Antenna Performance

The antenna reached its desired resonance at 2.400 GHz after completing the parametric optimization process which proved correct patch design and feed system measurements. The corresponding patch width (Wp) = 38.04mm and length of patch (Lp) = 29mm where accurate performance parameters have been observed.

Return Loss S11

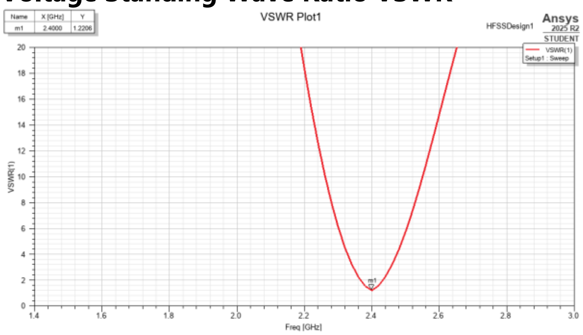


S11 Plot

From the figure 9, optimized antenna shows minimum return loss of -20dB at 2.4GHz. The impedance matching between antenna and 50Ω feed line shows excellent performance according to this finding. More than 99% of power transfers across the system while only minimal power reflects back.

The -10dB bandwidth records a range from 2.36 GHz to 2.44 GHz. The resulting bandwidth from 2.44 to 2.36 the bandwidth reaches 0.08GHz = 80MHz. The optimization process improved bandwidth because it improved both impedance matching and frequency stability. The 2.4GHz ISM band required for Wi-Fi WLAN and Bluetooth applications can be fully covered by this bandwidth.

Voltage Standing Wave Ratio VSWR



VSWR Plot

From the given figure 10, VSWR Plot of optimized antenna achieves minimum VSWR of 1.22 at 2.4GHz which meets the standard requirement that permits values up to 2. This tells that efficient power has been transferred from feed line to the antenna. The system shows dependable functionality according to this finding.

The optimized antenna achieves accurate desired frequency confirming parametric optimization was successful. The improvement was achieved through adjustment of patch length and width. Which directly affects the effective electrical length.

Table II. Comparison Of Preformnce Parameters

Parameter	*Initial Design*	*Optimized Design*	*Final Optimized Design*
Resonant Frequency	2.378 GHz	2.424 GHz	2.400 GHz
Return Loss	-14.43dB	-21.21dB	-20.6dB
VSWR	0.80	1.51	1.22
Bandwidth	44 MHz	75.7 MHz	80 MHz

V. CONCLUSION

The researchers developed and optimized their rectangular microstrip patch antenna which operates at the 2.4 GHz frequency. The researchers used an FR4 substrate which had a thickness measurement of 1.6 mm. The researchers used standard transmission line model equation to determine the initial antenna dimensions which served as their theoretical starting point. The system demonstrates resonance characteristics that approach the target frequency range with moderate impedance matching and efficient power delivery but it presents a minor frequency deviation.

The researchers performed parametric optimization through full wave electromagnetic simulation which they executed in ANSYS HFSS to overcome this restriction. The researchers achieved 2.4 GHz resonance through patch dimension modifications. The optimized antenna showed significant improvement in the return loss which reached nearly -20.06dB, and achieved a VSWR of 1.22, which demonstrated efficient impedance matching and minimal signal reflection. The antenna demonstrated a bandwidth capacity of approximately 80 GHz, which allowed it to operate continuously and dependably from 2.4 GHz to 2.5 GHz within the ISM band. The system achieves effective radiation performance which meets the requirements for actual wireless communication systems.

The results demonstrate that precise dimensioning combined with parametric optimization leads to better results while keeping building expenses and production expenses at their existing levels. The complete antenna system functions as a compact and cost-efficient solution which meets the needs of wireless communication systems working in 2.4 GHz. The research team plans to create physical products and execute testing operations which will authenticate simulated outcomes, while they subsequently assess radiation efficiency and polarization characteristics.

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