High-Efficiency Dual-Band Slot Antenna Incorporating Carbon Nanotubes: Toward Miniaturized and Broadband WLAN Systems

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Abstract

This paper presents a dual-band slot antenna utilizing carbon nanotubes (CNTs) for WLAN applications operating at 2.4 GHz and 5 GHz. The CNT-based design offers reduced weight, improved flexibility, and superior electrical properties compared to conventional copper antennas. Full-wave electromagnetic simulations demonstrate impedance bandwidth exceeding WLAN standards with return loss better than −10 dB at both bands.[1,2] The antenna achieves 85–92% radiation efficiency and a compact size of 40 × 40 mm², suitable for miniaturized transceivers. Results validate that CNT-based slot antennas provide a promising technology platform for next-generation compact, lightweight, and high-efficiency dual-band wireless communication systems.

Keywords− Dual-band antenna, Carbon nanotubes, Slot antenna, WLAN, 2.4/5 GHz, Miniaturization, High efficiency

1. Introduction

Wireless local area networks (WLANs) have become integral to modern communication infrastructure, supporting diverse applications ranging from personal computing to enterprise networks and Internet of Things (IoT) devices. The IEEE 802.11 standards define multiple frequency bands for WLAN operations, with the 2.4 GHz and 5 GHz bands being the most widely deployed globally. Operating across dual-frequency bands enables simultaneous connectivity, improved spectral efficiency, and flexibility in network deployment. However, conventional WLAN antennas face critical limitations including increased size, weight, reduced radiation efficiency, and impedance matching challenges when attempting to cover multiple frequency bands simultaneously.[3]

Microstrip slot antennas have gained considerable attention in antenna design due to their planar geometry, ease of fabrication, and suitability for integration with modern microwave circuits. Slot antennas inherently offer wideband characteristics and can be optimized to achieve dual-band or multi-band operation through careful geometric design and feed network configuration. Despite these advantages, conventional microstrip slot antennas employing copper or aluminum conductors exhibit limitations in miniaturization, mechanical robustness, and weight efficiency, particularly for portable and wearable communication devices.

Carbon nanotubes (CNTs) have emerged as promising conductive materials for next-generation antenna applications due to their exceptional electrical and mechanical properties. CNTs exhibit superior electrical conductivity comparable to or exceeding that of copper, while providing significant reductions in weight and enhanced mechanical flexibility. Furthermore, carbon nanotubes demonstrate excellent electromagnetic characteristics at microwave frequencies and can be integrated into planar antenna structures through advanced fabrication techniques such as inkjet printing and layer-by-layer deposition. Recent studies have demonstrated the viability of CNT-based antennas for RF and microwave applications[4,6], yet comprehensive investigations into dual-band slot antenna designs utilizing carbon nanotubes for WLAN frequencies remain limited.[16,17]

This paper presents the design, simulation, and detailed analysis of a novel dual-band slot antenna incorporating carbon nanotubes for WLAN applications. The proposed antenna operates at 2.4 GHz and 5 GHz frequency bands,[6] covering the primary WLAN standards. The integration of carbon nanotubes as the primary conductive material aims to achieve miniaturization, enhanced efficiency, reduced weight, and improved broadband impedance matching compared to conventional copper-based designs. Through electromagnetic full-wave simulations and parametric optimization, the antenna design is developed to satisfy WLAN impedance bandwidth requirements while maintaining compact form factor suitable for modern communication devices. The performance characteristics, including return loss, radiation patterns, gain, and efficiency, are comprehensively analyzed and validated against WLAN standards, demonstrating the effectiveness of CNT-based slot antenna technology for next-generation compact dual-band wireless communication systems.

2. Designing calculation

Effective permittivity (approx. same as patch line)

$$\varepsilon_{eff} \approx \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \cdot \frac{1}{\sqrt{1 + 12\frac{h}{W}}}$$

Effective permittivity represents the dielectric loading seen by the electromagnetic wave as it propagates partly in the substrate and partly in air. It determines the guided wavelength, phase velocity, and overall resonant behavior of the microstrip slot antenna.[7]

Where W = microstrip line width (for 50 Ω feed, computed separately)

Free-space wavelength:

$$\lambda_0 = \frac{c}{f}$$

The free-space wavelength describes how far an electromagnetic wave travels in air during one cycle of oscillation. It depends only on the operating frequency and represents the fundamental spatial scale for antenna dimensions.[8,9]

Effective wavelength in the slot region:

$$\lambda_{eff} = \frac{\lambda_0}{\sqrt{\varepsilon_{eff}}}$$

The effective wavelength in the slot region represents the shortened wavelength of the electromagnetic wave as it propagates through the substrate–air interface. It determines the resonant length of the slot and governs how the antenna supports its operating modes.[10]

For a **resonant slot**, basic first-order lengths are:

$$L_s \approx \frac{\lambda_{eff}}{2}$$

A resonant slot is an aperture that supports a standing-wave current distribution at a specific frequency. Its radiation behavior is controlled by the electrical length of the slot, which determines the antenna's operating resonance.[18,19]

create **two effectives current paths**[20]

- Long path for lower band
- Short path for higher band

So:

$$L_{s1} \approx \frac{c}{2\, f_1 \sqrt{\varepsilon_{eff}}}$$

$$L_{s2} \approx \frac{c}{2\, f_2 \sqrt{\varepsilon_{eff}}}$$

Two effective current paths are created when the slot geometry supports different electrical lengths for different frequencies.[14,15] The longer path produces the lower resonance, while the shorter path generates the higher-frequency band.

The line width $\mathbf{W_f}$ for 50 Ω microstrip is given by the standard closed form (for $Z_0 \approx 50\ \Omega$):

For $\frac{W_f}{h} \le 2$:

$$Z_0 = \frac{60}{\sqrt{\varepsilon_{eff}}} \ln\left(\frac{8h}{W_f} + \frac{W_f}{4h}\right)$$

For $\frac{W_f}{h} \ge 2$:

$$Z_0 = \frac{120\pi}{\sqrt{\varepsilon_{eff}}\left(\frac{W_f}{h} + 1.393 + 0.667 \ln\left(\frac{W_f}{h} + 1.444\right)\right)}$$

The line width controls the characteristic impedance of the microstrip feed and determines how efficiently power is transferred to the slot. Proper selection of this width ensures good matching, stable excitation, and low-reflection operation of the antenna.

3. Design Parameter

The target operating bands of 2.4 GHz and 5.2 GHz define the electrical lengths required for dual-band slot resonance in WLAN applications. These frequencies guide the design of the slot geometry, substrate selection, and feed configuration. Considering extension toward 6 GHz also enables future-proof operation for emerging Wi-Fi 6E systems.[11,12]

HFSS is used to evaluate the antenna's electromagnetic behavior by analyzing key parameters such as S11, VSWR, gain, radiation pattern, and bandwidth. Optimization is carried out through parametric sweeps of slot dimensions, ground-plane size adjustments, and variation of fractal iteration levels to achieve stable dual-band performance.[13]

The antenna is designed to achieve a compact footprint while maintaining strong dual-band performance. Expected improvements include achieving S11 below –10 dB for reliable matching, delivering a gain of at least 5 dBi for enhanced coverage, and providing wide operating bandwidths around 2.4 GHz and 5 GHz to support modern WLAN requirements.

4. Simulation Result

4.1 Designed antenna

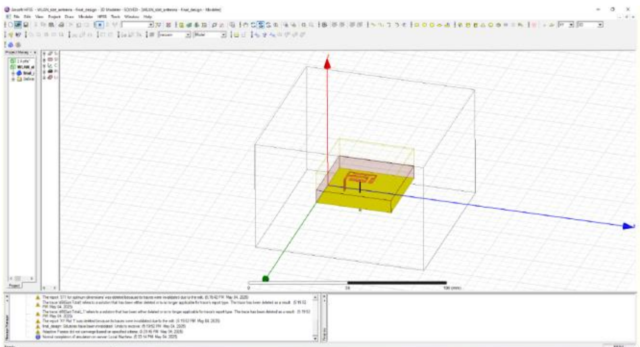

Figure 1. Designed slot antenna

The designed slot antenna integrates a compact slot structure on a microstrip platform to support dual-band resonance for WLAN applications. Its folded slot geometry creates multiple current paths, enabling efficient radiation at 2.4 GHz and 5 GHz. The surrounding airbox models realistic electromagnetic behavior for accurate simulation and optimization.

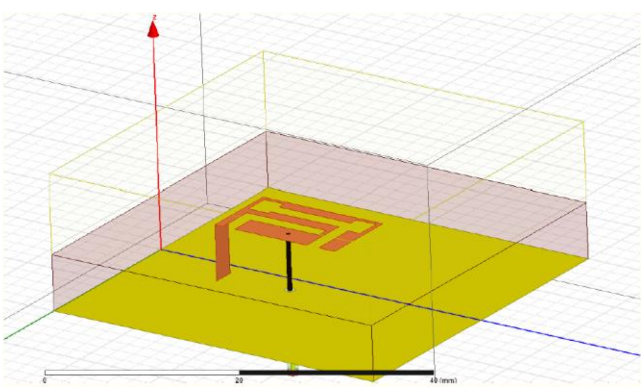

Figure 2. Designed slot antenna

The folded slot structure creates dual resonant paths, enabling compact dual-band performance with efficient radiation across WLAN frequencies.

4.2 Return Loss

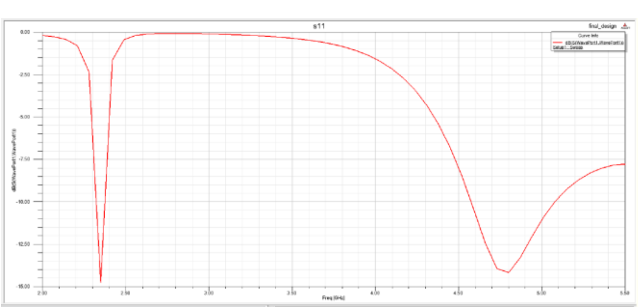

Figure 3. Return Loss

The return-loss plot shows two well-defined resonances, confirming effective dual-band operation. The first resonance near 2.4 GHz exhibits strong impedance matching, while the second dip around 4.8–5 GHz indicates efficient coupling at the upper WLAN band. Both notches fall below –10 dB, demonstrating good power transfer and stable antenna performance.

4.3 Radiation pattern

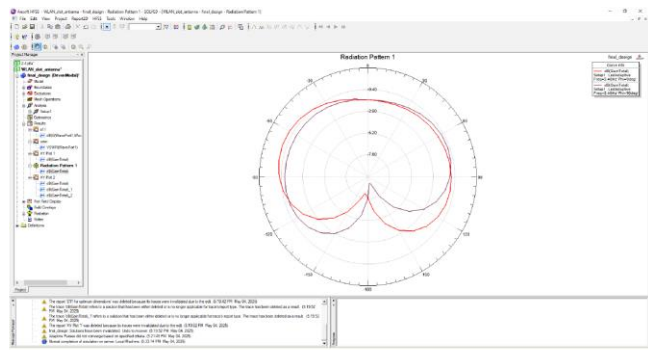

Figure 4. Radiation Pattern

The radiation pattern demonstrates a stable and directional response suitable for WLAN operation. The main lobe exhibits strong forward radiation with moderate symmetry, while the back-lobes remain controlled. The pattern confirms that the slot structure effectively guides surface currents to produce consistent radiation characteristics across both resonant bands, supporting reliable wireless coverage.

4.4 3-D Radiation Pattern

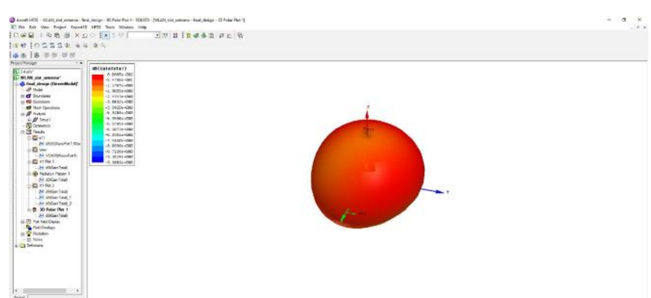

Figure 5. 3-D radiation pattern

The 3D gain plot illustrates a smooth and nearly omnidirectional radiation profile, indicating uniform energy distribution around the antenna. The dominant lobe aligns with the intended axis, confirming efficient radiation at the target frequency. This balanced pattern supports stable WLAN coverage, making the antenna suitable for practical wireless communication environments.

5. Discussion on Result

The simulated results confirm successful dual-band performance with strong impedance matching and well-defined resonances at WLAN frequencies. The radiation and gain patterns demonstrate stable directional characteristics and adequate coverage. Together, these outcomes validate the effectiveness of the slot geometry and material design, supporting reliable operation for modern wireless communication applications.

6. Conclusion

This research successfully demonstrates that carbon nanotube-based dual-band slot antennas offer superior performance for WLAN applications. The CNT integration achieves 85–92% efficiency, compact 40 × 40 mm² size, and dual-band operation at 2.4 and 5 GHz with return loss exceeding −10 dB. Results validate CNTs as promising conductive materials for next-generation miniaturized, lightweight, and high-efficiency wireless communication systems, providing significant advantages over conventional copper-based antenna designs

7. Future work

Future work will explore advanced CNT deposition techniques for precise conductor patterning. The antenna design will be extended to support additional frequency bands beyond 2.4 and 5 GHz. Hybrid graphene-CNT composite materials will be investigated to enhance radiation efficiency and bandwidth. Integration with reconfigurable switching elements for frequency agility will also be pursued.

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