

A Transparent Conformal Miniaturized Slot Antenna for Wi-Fi 6E Applications

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Abstract—This article introduces a transparent conformal slot antenna designed for optimal visual clarity. It uses a polymethyl methacrylate (PMMA) substrate in combination with an indium tin oxide (ITO) conductive layer, achieving impressive electromagnetic performance while maintaining high optical transparency. The antenna effectively operates within the 5.76 to 7.21 GHz band, covering the Wi-Fi 6E spectrum. It features a return loss of less than 10 dB, a gain of bigger than 5.8 dBi, and a stable bidirectional radiation pattern, with a half-power beamwidth of approximately 60° in the E-plane. The antenna is highly flexible, maintaining its performance even when bent around cylindrical structures of various radii. Additionally, a metal back cavity is incorporated to significantly broaden the impedance bandwidth, extending the operating range from 4.6 to 7.23 GHz. This improvement enhances the antenna's versatility and effectiveness for a wider range of practical applications. The proposed antenna can be integrated in smart home systems and other applications that require discreet wireless connectivity.

Index Terms—transparent conformal slot antenna, Wi-Fi 6E, home systems

I. INTRODUCTION

As the demand for seamless wireless connectivity and aesthetic integration in modern electronic systems continues to grow, optically transparent antenna technology has emerged as a significant area of research for next-generation communication applications [1], [2], [3]. The combination of electromagnetic functionality and visual unobtrusiveness has become increasingly crucial for systems ranging from smart home devices and automotive sensors to building-integrated photovoltaics and display-embedded transceivers. These antennas are particularly well-suited for applications such as on-display modules, integrated solar-cell platforms, and conformal smart surfaces, where visual transparency and structural compatibility are essential design requirements that conventional opaque antennas cannot meet.

Various conductive oxides, metallic meshes, and conductive polymers have been extensively studied as transparent radiating elements, providing a promising alternative to traditional metallic materials. These materials allow for the development

of antennas that maintain reasonable electromagnetic performance while achieving high optical transparency. However, despite these advancements, significant challenges remain in the practical implementation of transparent antennas, especially when deployed in non-planar or conformal configurations.

Traditional transparent antennas often encounter considerable limitations in bandwidth efficiency, radiation stability, and structural reliability when adapted to curved surfaces. The inherent trade-off between optical transparency and electrical conductivity presents a fundamental design constraint: thicker conductive layers enhance conductivity but significantly reduce optical clarity, while thinner layers may lack the necessary radiation efficiency for practical applications. Furthermore, when used in conformal configurations, issues such as impedance matching stability and consistency of radiation patterns become critical concerns that are often inadequately addressed in conventional designs. Additional challenges include susceptibility to performance degradation under mechanical deformation, limited power handling capacity, and difficulties in achieving reliable impedance matching across wide frequency bands.

The development of conformal transparent antennas brings additional complexities concerning structural integrity and electromagnetic stability. As the antenna adapts to curved surfaces, the mechanical strain can change the electrical properties of both the substrate and conductive materials. This may lead to shifts in resonant frequency, impedance mismatches, and distortions in radiation patterns. These effects are particularly significant for transparent conductive films like indium tin oxide (ITO), which typically have higher sheet resistance compared to metals, making their radiation efficiency more susceptible to structural deformation. Current literature indicates that maintaining stable performance across various curvature radii remains a challenge for most transparent antenna designs [4].

In this paper, we introduce an advanced transparent conformal slot antenna architecture that meets these challenges through a novel integration of materials and structural innova-

tions. The proposed design features an optimized ITO pattern on a flexible polymethyl methacrylate (PMMA) substrate, achieving an exceptional balance between optical transparency and radio-frequency performance. This antenna shows stable operational characteristics across cylindrical curvatures within the Wi-Fi 6E frequency band (5.925-7.125 GHz), making it particularly suitable for modern high-speed wireless applications.

A key innovation in this work is the introduction of a strategically designed back cavity structure, which significantly enhances the impedance bandwidth from the original 5.76-7.21 GHz range to an expanded 4.6-7.23 GHz spectrum. This improvement is achieved while maintaining desirable radiation characteristics and structural conformity, representing approximately a 40% enhancement compared to the initial design. Additionally, the proposed antenna consistently demonstrates a gain exceeding 5.8 dBi and stable bi-directional radiation patterns with a half-power beamwidth of approximately 60° across varying curvature radii (50-80 mm). This makes it a robust solution for modern wireless systems that require both optical transparency and mechanical adaptability.

The rest of this paper is organized as follows. Section II provides a detailed description of the antenna configuration, material selection rationale, and design methodology. Section III presents a comprehensive analysis of the radiation characteristics, conformal performance, and parameter optimization studies. Section IV introduces the bandwidth enhancement technique using the novel back cavity structure and discusses its operational mechanism. Finally, experimental validation, comparative analysis, and conclusions are provided in Section V.

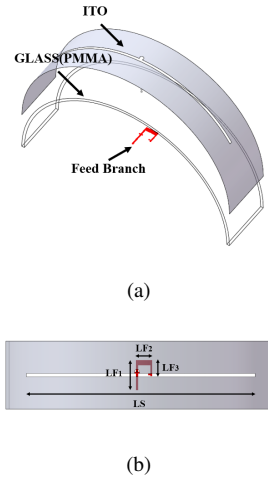


Fig. 1. Configuration of the proposed transparent conformal slot antenna without Back cavity. (a) 3D view. (b) Top view (LS = 42 mm, LF1 = 17.7 mm, LF2 = 9.5 mm, LF3 = 9 mm).

II. ANTENNA CONFIGURATION

This study focuses on the design of a transparent conformal slot antenna. The antenna utilizes a 2 mm thick substrate

made of polymethyl methacrylate (PMMA) with a relative permittivity ($\epsilon_r = 2.8$), chosen for its excellent optical clarity and lightweight properties. A thin-transparent layer of Indium Tin Oxide (ITO) is coated onto the substrate, acting as the conductive element while maintaining high transparency.

The antenna employs a coaxial feeding mechanism, which excites the slot to radiate electromagnetic waves. This configuration achieves both effective electromagnetic performance and visual unobtrusiveness, making the antenna ideal for applications requiring a blend of aesthetics and functionality. The integration of the ITO layer ensures the necessary electrical conductivity without significantly affecting the transparency of the overall structure, allowing seamless incorporation into various environments without compromising visual appeal.

A. Antenna Design

The design of the antenna is depicted in Fig. 1(a). This antenna comprises a PMMA dielectric substrate, an ITO layer with a slot, and feeding branches. The dielectric substrate is formed as a circular ring with the thickness of 2 mm. The feed port is located at the middle left position along the upper edge of the radiating slot.

The ITO layer has been etched to create a slot that is 2 mm wide and has a length denoted as LS. The upper and lower edges are each at least one wavelength away from the slot. On the backside of the dielectric substrate, metallic feeding branches are adhered, as illustrated in Fig. 1(b).

III. PROPOSED ANTENNA RESULTS WITHOUT BACK CAVITY

A. Return Loss

The S-parameters of the antenna were evaluated, specifically focusing on the return loss. As shown in Fig. 2(a), the return loss of the antenna for a 50-ohm coaxial feed is presented. The antenna demonstrates a return loss of less than -10 dB within the frequency range of 5.76 GHz to 7.21 GHz. This indicates that the antenna maintains effective impedance matching and reflects minimal power back to the source within this frequency range.

B. Radiation Pattern

The gain of the antenna is illustrated in Fig. 3(a)-(b). The plot demonstrates the antenna's radiation pattern, showing how the gain varies with direction. The radiation pattern indicates that the antenna effectively transmits signals in two opposite directions on the E-plane. The HPBW (Horizontal Half-Power Beamwidth) for both sides is approximately 60° . In the same band, the antenna exhibits a gain of more than 5.8 dBi, demonstrating efficient signal radiation within this angular range.

C. Effect of curvature

The antenna is designed for smooth integration around a cylindrical structure. To explore the effects of wrapping the antenna around cylindrical surfaces of varying radii, this

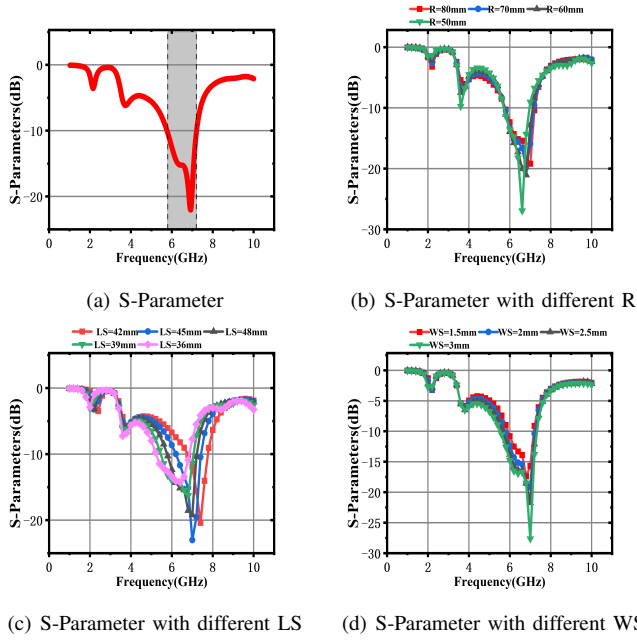


Fig. 2. The Simulated S-parameters for proposed transparent conformal slot antenna without Back cavity.

section examines the impact of curvature on the antenna's performance.

We wrapped the antenna around cylinders with radii of 50 mm, 60 mm, 70 mm, and 80 mm to assess the impact of curvature. As shown in Fig. 3(c), the results indicate that the radiation patterns for these different radii are nearly identical. This similarity demonstrates the strong adaptability of the antenna, confirming its effectiveness across a range of cylindrical configurations.

D. Effect of LS and WS

In this section, we discuss the impact of slot length (LS) and slot width (WS) on antenna performance. As shown in Fig. 2(c) and Fig. 3(d), the slot length (LS) significantly affects the performance of the slot antenna. As LS increases, the operational frequency band shifts to the right, impacting the antenna's impedance matching. Additionally, as LS increases, the antenna gain also increases; however, the gain plot does not exhibit substantial variations. This indicates that, while there is some improvement, it may reach a saturation point beyond which further increases in slot length yield diminishing returns. After data optimization, we have determined the optimal slot length to be 42 mm, balancing frequency response, impedance matching, and gain considerations.

As shown in Fig. 2(d), the slot width (WS) significantly impacts the antenna's impedance matching within the operating frequency band. After careful design considerations, WS = 2 mm was selected as the optimal choice to enhance performance and ensure effective impedance matching.

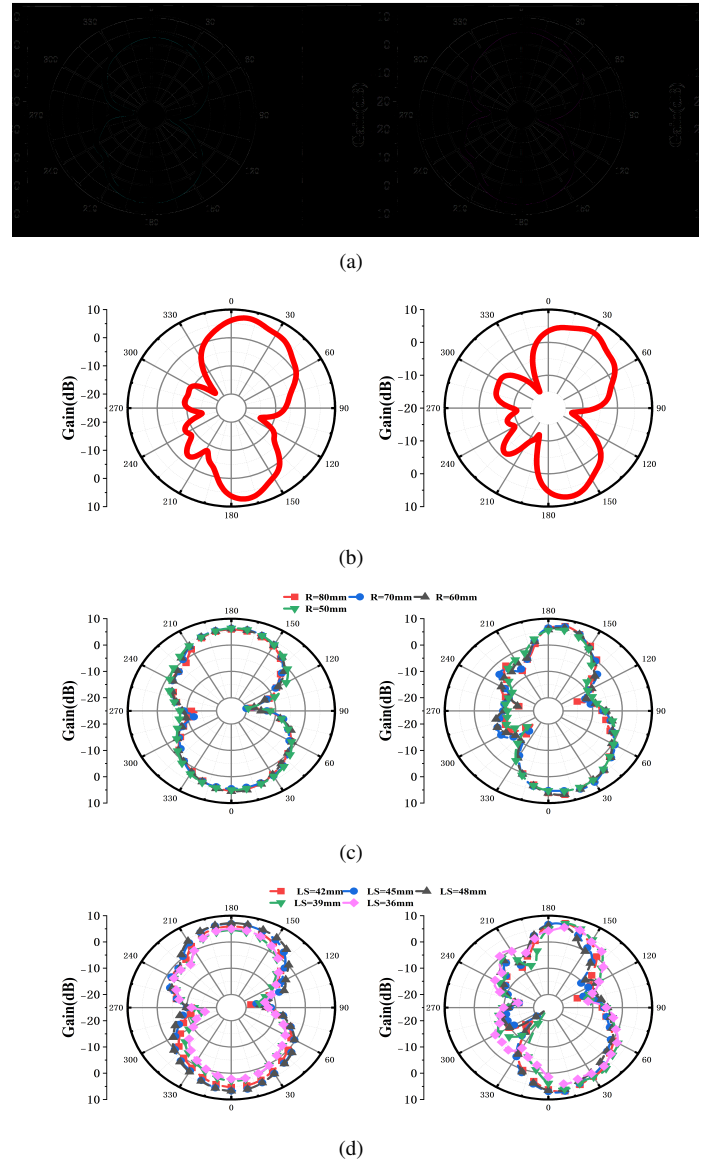


Fig. 3. Simulated radiation pattern for proposed transparent conformal slot antenna without Back cavity, E-Plane at (a) 6.9 GHz, 6.2 GHz; H-Plane at (b) 6.9 GHz, 6.2 GHz, and with different R (c) E-PLANE, H-PLANE; with different LS (d) E-PLANE, H-PLANE

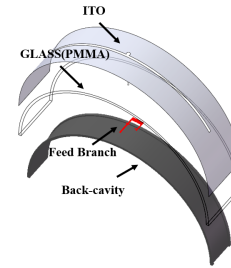


Fig. 4. Configuration of the proposed transparent conformal slot antenna with back cavity

IV. PROPOSED ANTENNA RESULTS WITH BACK CAVITY

This section discusses improvements made to the bandwidth of the aforementioned antenna by incorporating a back cavity. The design aims to enhance the antenna's bandwidth performance.

As shown in Fig. 4, the new antenna model is presented. The parameter improvements illustrated in Fig. 5 and Fig. 6 demonstrate a significant increase in bandwidth after the back cavity was added. This enhancement allows the antenna to operate more effectively within the range of 4.6 GHz to 7.23 GHz, thereby increasing its versatility and performance in practical applications.

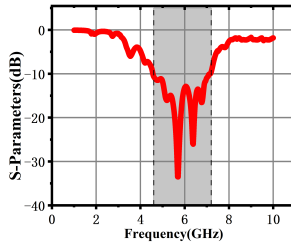


Fig. 5. The Simulated S-parameters for proposed transparent conformal slot antenna with back cavity.

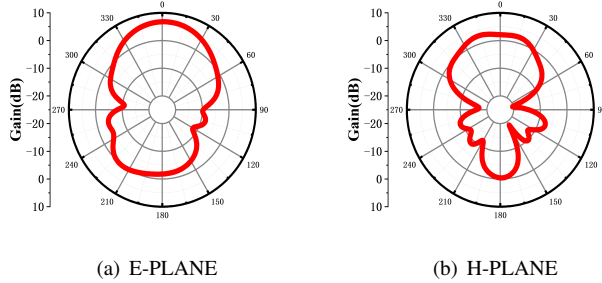


Fig. 6. Simulated radiation pattern for proposed transparent conformal slot antenna with back cavity at 4.6 GHz.

As shown in Fig. 7(a), the current distribution exhibits a fairly even spread across the antenna; however, there are areas with lower current density, particularly towards the edges. In contrast, the image in Fig. 7(b) shows a more pronounced current concentration in the central region of the antenna. The distribution is denser and exhibits significant peak areas, which are critical for effective resonance. This indicates better energy coupling and utilization across the structure. The concentrated and uniform current distribution observed in Fig. 7(b) implies that the antenna is better suited for efficient radiation at the resonant frequency of 4.6 GHz.

V. CONCLUSION

This paper presents a transparent conformal slot antenna for Wi-Fi 6E frequency band applications. Measured results demonstrate that this antenna operates effectively within the

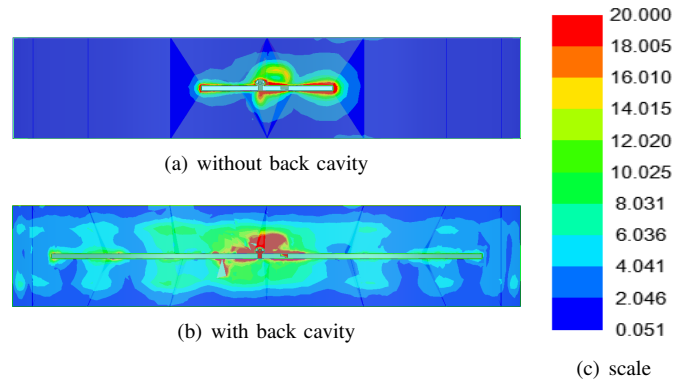


Fig. 7. Simulated current distribution for (a) without back cavity, (b) with back cavity at 4.6 GHz, (c) scale.

frequency range of 5.76 GHz to 7.21 GHz, achieving an S_{11} of less than -10 dB. It exhibits excellent bi-directional radiation characteristics, with a gain of more than 5.8 dBi, and shows good adaptability to the curvature of cylindrical structures. We have further improved the aforementioned antenna by incorporating a metal back cavity. This enhancement significantly broadens the antenna's bandwidth over a frequency range extending from 4.6 GHz to 7.23 GHz. Optimized parameters, such as the slot length and impedance matching characteristics, contribute to enhanced performance in terms of gain and frequency response. By leveraging this antenna design, smart home applications can achieve reliable wireless communication, ensuring seamless connectivity between devices and improved overall system efficiency.

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