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Substrate Integrated Waveguide Slot Antenna for 5G Application

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Abstract

This research presents the design and analysis of a Substrate Integrated Waveguide (SIW) based slot antenna for high-frequency microwave applications. The antenna structure is developed on a Rogers 5880 substrate with a relative permittivity (εr) of 4.4 and a thickness of 0.6 mm, offering low dielectric losses and stable performance. The SIW cavity is formed using periodic metallic vias with a radius of 0.25 mm and a pitch of 0.8 mm, ensuring effective confinement of the guided wave. A longitudinal slot is etched on the top metallic plane to enable efficient radiation. The overall dimensions of the SIW are 17 mm in length and 8 mm in width, making the antenna compact and suitable for integration in planar circuits. The proposed SIW slot antenna exhibits desirable characteristics such as directional radiation, low profile, and high efficiency, making it promising for applications in wireless communication, radar systems, and compact RF front-ends.

Keywords: Substrate Integrated Waveguide, Defected Ground Structure, Computer Simulation Technology; Printed Circuit Board, Multiple-Input Multiple-Output, Leaky-Wave Antennas.

1. Introduction

The 5G necessitates high-frequency operation, but this presents challenges like increased propagation loss. Substrate Integrated Waveguide (SIW) technology offers a promising solution, by enabling low-profile, high-gain, and wideband antennas. SIW slot antennas, particularly, are attractive for 5G due to their design flexibility and performance

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optimization. CST Microwave Studio is used to accurately predict and improve the iterative design of the antenna. The expansion of 5G technology necessitates advanced communication systems operating at millimeter-wave (mmWave) frequencies. To meet the demands for high data rates, minimal latency, and broad bandwidth, 5G networks require efficient, compact, and affordable components. Substrate Integrated Waveguide (SIW) technology offers a compelling solution. SIW merges the benefits of conventional metallic waveguides with the adaptability of planar circuits, facilitating the creation of compact, high-performance structures suitable for mmWave applications. This is achieved by constructing waveguide-like structures on printed circuit boards (PCBs) using arrays of metallic vias to confine electromagnetic waves. This design is particularly advantageous for 5G systems, which require components with low signal loss, and communication. The primary objective of this work is to design and analyze a compact and efficient Substrate Integrated Waveguide (SIW) based slot antenna using Rogers 5880 substrate, aimed at high-frequency microwave applications. The design focuses on optimizing key parameters such as via pitch, via radius, substrate thickness, and slot dimensions to achieve effective wave confinement, low insertion loss, and high radiation efficiency. The study also aims to evaluate the performance of the antenna in terms of return loss, bandwidth, and radiation pattern through full-wave electromagnetic simulations, ensuring its suitability for integration into modern RF and wireless communication systems.

2. Literature Survey

This survey delves into the existing body of research to understand the evolution of SIW technology, particularly concerning its application in the millimeter-wave frequencies essential for 5G.

Yang and Rahmat-Samii [1] demonstrated the effectiveness of EBGs in isolating antenna elements, thereby enhancing the overall performance of the array, particularly in terms of radiation patterns and efficiency for various array applications. Mu'ath, Denidni, and Sebak [2] focused on the design and implementation of a compact EBG structure specifically customized for millimeter-wave frequencies. Their research highlighted the ability of this compact EBG design to significantly reduce mutual coupling between antenna elements in densely packed arrays operating at these high frequencies, which are essential for emerging communication technologies.

Liu, Jackson, and Long [3] explored the design and radiation characteristics of a substrate-integrated waveguide (SIW) leaky-wave antenna that utilizes transverse slots as radiating elements. This study provided insights into how the dimensions and arrangement of these slots influence the antenna's radiation pattern and leakage properties, contributing to the understanding of SIW-based leaky-wave antenna design. Ettorre, Sauleau, and LeCoq [4] presented a sophisticated multi-beam, multi-layer leaky-wave antenna based on SIW pillbox technology, specifically developed for millimeter-wave applications. Their work showcased the antenna's capability to generate multiple independent beams, offering enhanced flexibility and capacity for advanced communication systems operating at high frequencies.

Taravati and Caloz [5] introduced a novel leaky-wave antenna system that integrates the functionalities of a mixer, duplexer, and antenna into a single structure through periodic space-time modulation. This innovative approach demonstrated the potential for highly integrated RF front-ends with unique signal processing and radiation control capabilities. Taravati and Caloz [6] further explored the concept of space-time modulation in leaky-wave antennas, demonstrating a system capable of nonreciprocal mixing, amplification, and beam scanning. This research highlighted the advanced control over electromagnetic waves achievable through dynamic modulation of the antenna's properties.

Alibakhshikenari et al. [7] investigated the electromagnetic interaction between closely packed antenna elements in an array when a metasurface is employed as a superstrate or decoupling structure. Their study provided valuable insights into how metasurfaces can be used to manage mutual coupling in compact arrays, which is essential for applications like MIMO systems and synthetic aperture radars. Yang et al. [8] presented a method to enhance isolation between elements in a patch antenna array by strategically incorporating a fractal Unit Cell EBG (UC-EBG) structure in combination with a cross slot etched on the patch. This hybrid approach demonstrated improved decoupling and overall array performance.

Gupta et al [9] introduces a novel dual-band monopole planar antenna designed for 28/38 GHz 5G bands, achieving bandwidths of 0.5/0.7 GHz and high radiation efficiency (>94%). The antenna demonstrates a stable omni-directional radiation pattern with high gain, validated through simulation (ANSYS HFSS) and fabrication on a Rogers RT/Duroid 5880 substrate, showing good agreement between the two. The authors propose this design as a simple and miniaturized solution for future millimeter-wave 5G communication systems.

Qin et al. [10] presents a compact dual-band MIMO antenna designed for WLAN applications at 2.4/5.2 GHz, focusing on achieving high port isolation. The antenna utilizes two monopole elements, with isolation enhanced by a T-shaped junction on the substrate's top and two ground plane slots. The measured bandwidths (2.34-2.55 GHz and 5.13-5.85 GHz) cover the WLAN bands, and the isolation between the ports is maintained above 20 dB in both bands. The antenna also demonstrates a low envelope correlation coefficient (ECC < 0.001), indicating good diversity performance. The simulated and experimental results show good consistency. The compact size of 38 mm × 43 mm × 1.6 mm makes this design suitable for space-constrained WLAN devices.

3. Proposed System

The proposed antenna design and fabrication will follow a five-step process, as depicted in Figure 1. First, the selection of the desired frequency range determines the antenna size and its performance. Second, a low-loss substrate material, Rogers 5880, is selected to ensure antenna efficiency. Third, the antenna is designed, and slots are etched as radiating elements for impedance and radiation control. Fourth, the parameters are optimized to achieve improved performance. Finally, the S-parameter and radiation pattern are visualized.

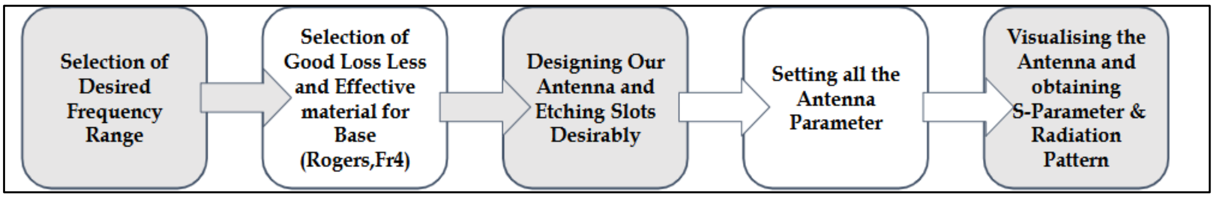


Figure 1. Flow of Antenna Design

Table 1. SIW Slot Antenna Design Parameters

S.No.	Parameters	Dimensions in (mm)
1.	Pitch	0.8
2.	Thickness	0.6

3.	Relative Permittivity (Er) Constant Value	0.44
4.	Material	Rogers 5880
5.	Radius of Vias	0.25
6.	Length	17
7.	Width	8

Table 1 presents the design parameters for a Substrate Integrated Waveguide (SIW), a planar waveguide technology that similar to the traditional rectangular waveguides. The parameters include a pitch of 0.8 mm, a thickness of 0.6 mm, a relative permittivity (εr) of 4.4, a material of Rogers 5880, a via radius of 0.25 mm, a length of 17 mm, and a width of 8 mm. These parameters are essential for determining the SIW's operating frequency, bandwidth, and performance, with pitch and via radius affecting cutoff frequency, permittivity influencing wavelength, material impacting loss and stability, and length and width defining the size and resonant frequency.

The proposed SIW slot antenna with a U-shaped slot exhibits excellent 5G performance with low return loss, high efficiency, and a directional radiation pattern with a narrow beamwidth for focused transmission and reduced interference. The U-slot design allows for flexible manipulation of the radiation pattern through dimensional adjustments, essential for efficient 5G signal transmission and adaptive beamforming. The antenna's compact size, facilitated by both the SIW technology and the U-slot, enables integration into 5G devices. Additional benefits include low-loss propagation, good impedance matching, design simplicity, ease of fabrication (cost-effective), inherent shielding (improved EMC), and tunable resonant frequency for operation within 5G bands.

In Figure 2, the optimized U-slot design contributes to enhanced antenna gain, improving signal strength and coverage range. The ability to control the polarization of the radiated signal through U-slot manipulation further enhances the antenna's versatility. The design's robustness and stability make it suitable for deployment in various environmental conditions, ensuring reliable 5G communication. The integration of the U-slot into the SIW structure allows for the creation of compact antenna arrays, enabling multiple-input multiple-output (MIMO) functionality for enhanced data rates and capacity.

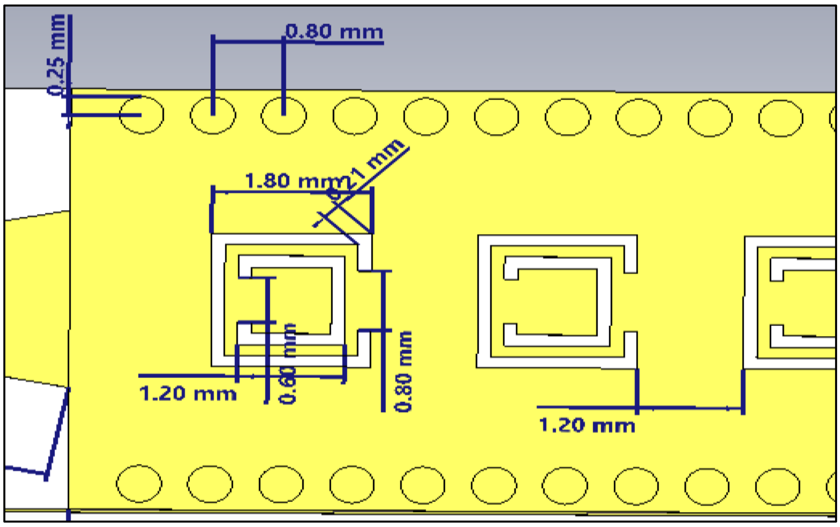


Figure 2. U Shaped Slot Dimensional Parameters

Figure 3 describes how the performance of the SIW slot antenna is influenced by the parameters of individual slots, such as their size, shape, and spacing. By carefully optimizing these parameters, it is possible to achieve desired radiation characteristics and impedance matching. The interaction between multiple slots can also significantly impact the overall antenna performance.

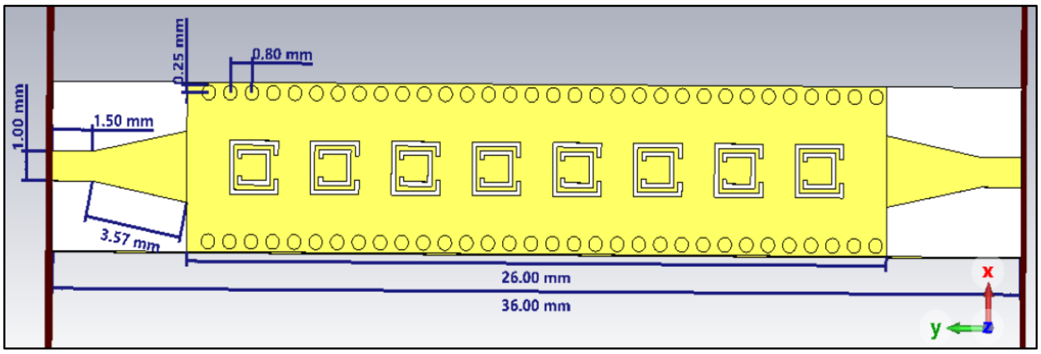


Figure 3. Front View of Slot Antenna

Figure 4 describes how the simulated results demonstrate that the proposed SIW slot antenna exhibits a highly directional radiation pattern with a narrow beamwidth. This characteristic is essential for 5G communication, as it enables focused energy transmission and minimizes interference from other signals. The narrow beamwidth also contributes to improved link reliability and signal quality, especially in dense urban environments where signal interference is a major concern.

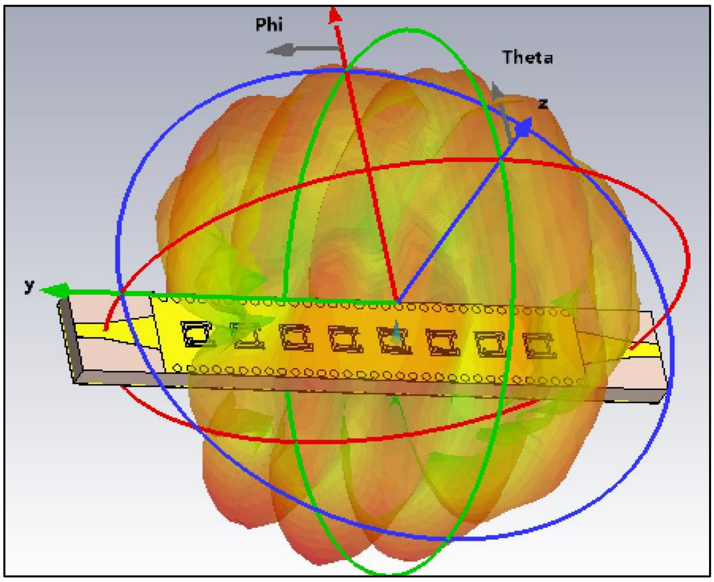


Figure 4. Radiation Pattern of the SIW Slot Antenna

4. Results and Discussion

4.1 S-Parameter

Figure 5 depicts the S-parameters, specifically S11, of the SIW (Substrate Integrated Waveguide) slot antenna, showing its return loss across a frequency range. The x-axis represents the Frequency in GHz, while the y-axis shows the S11 in dB. A lower S11 value indicates better impedance matching and less reflected power. A dip in the S11 curve around 28 GHz suggests that the antenna is designed to operate efficiently at this resonant frequency. The minimum S11 value reached is approximately -30 dB, indicating excellent return loss and minimal signal reflection at this frequency.

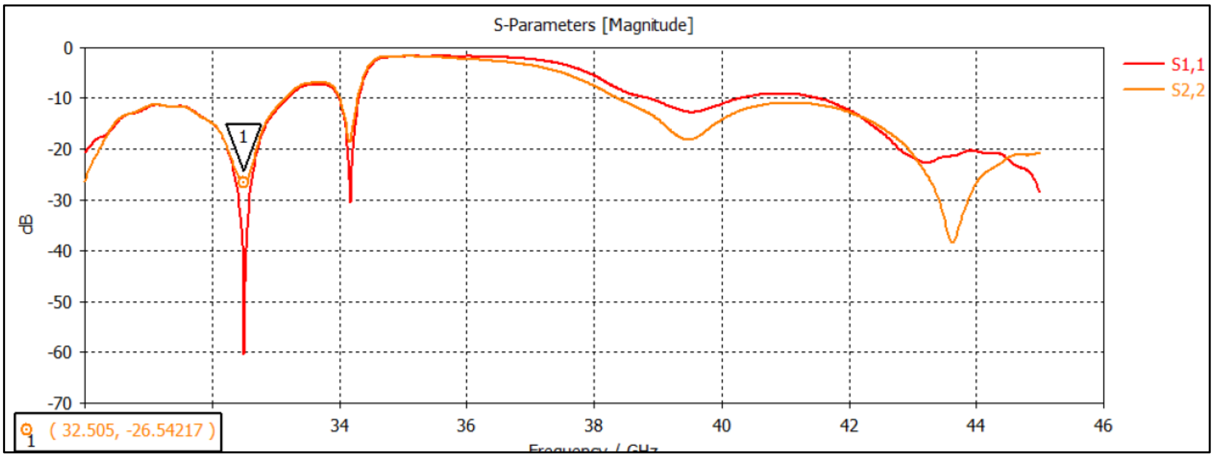


Figure 5. S-Parameters of SIW Slot Antenna

4.2 VSWR Analysis

Figure 6, illustrates the Voltage Standing Wave Ratio (VSWR) of the SIW slot antenna over a frequency range. The x-axis represents the Frequency in GHz, and the y-axis shows the VSWR. VSWR is a measure of impedance matching, with a lower VSWR indicating better matching. A VSWR of 1.0 is ideal, meaning no power is reflected. The graph shows a VSWR close to 1.0 around 28 GHz, confirming good impedance matching at the designed frequency. The VSWR remains below 2.0 within the operating bandwidth, ensuring efficient power transfer and minimal signal loss.

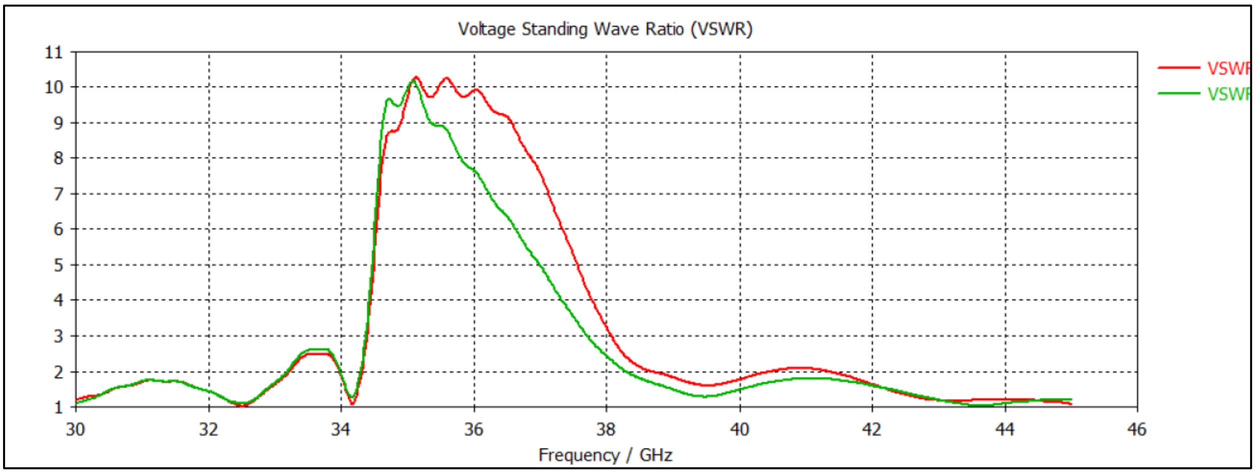
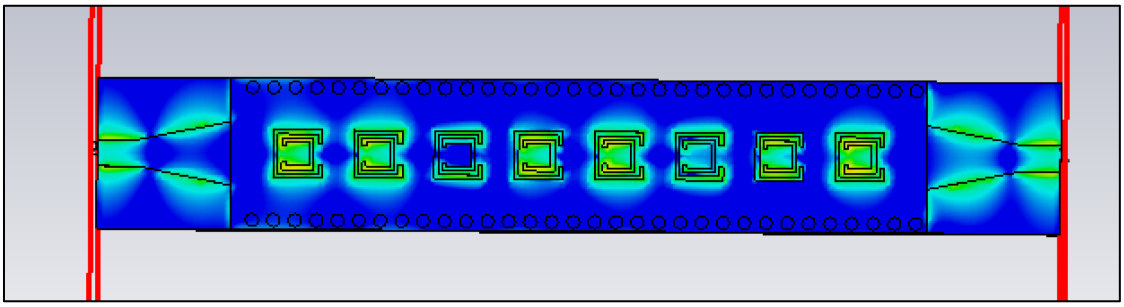


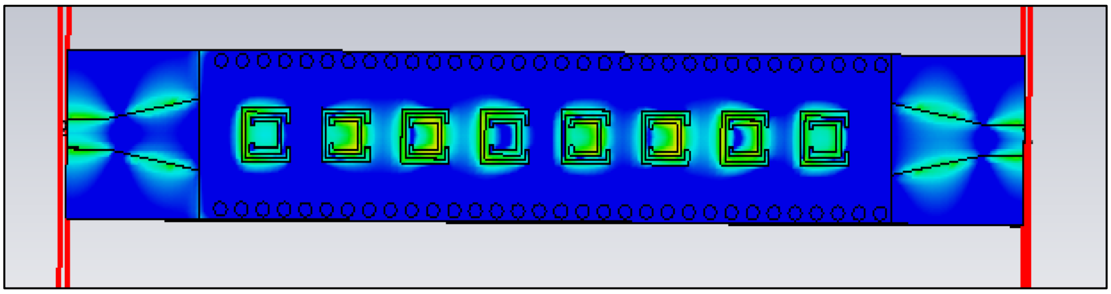
Figure 6. VSWR of SIW Slot Antenna

4.3 Electric Field and Magnetic Field Analysis

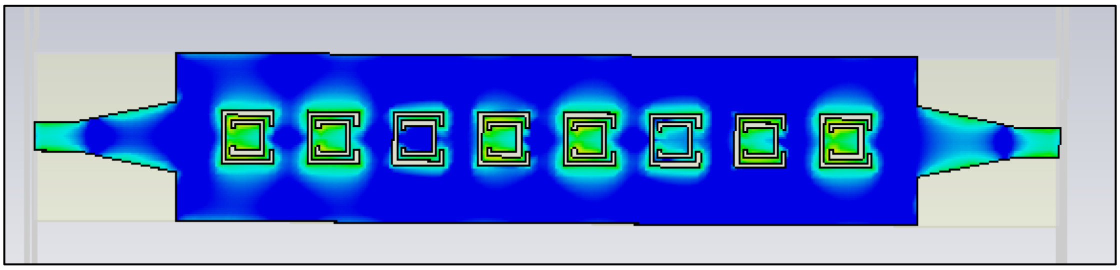
Figures 7 (a), (b), and (c) illustrate the electromagnetic field distributions of the SIW slot antenna. The top image shows the E-field (electric field) distribution, representing the intensity and direction of the electric field around the antenna. The middle image displays the surface current distribution, indicating the flow of current on the antenna's conductive surfaces. The bottom image shows the H-field (magnetic field) distribution, representing the intensity and direction of the magnetic field. The color gradients in these images indicate the field strength, with red typically representing higher intensity and blue representing lower intensity. These distributions are essential for understanding the antenna's radiation characteristics and performance.



(a)



(b)



(c)

Figure 7. (a) E Field (b) H Field and (c) Surface Current of SIW Slot Antenna

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From the Table 2 it is understood that the SIW design operates at 15.6 GHz with a 1.85 GHz bandwidth and 5.7 dB gain, exhibiting a 15-20 dB front-to-back ratio and 80-85% radiating efficiency. Electric and magnetic field strengths are specified at 1m (9.5 V/m, 0.025 A/m) and 0.1m (95-300 V/m, 0.25-0.8 A/m). These features indicate a directional and efficient SIW suitable for applications around 15.6 GHz.

Table 2. SIW Design Features

S.No.	Particulars	Numerical Values
1.	Operating Frequency	15.6GHz
2.	Bandwidth	1.85Hz
3.	Gain	5.7dB
4.	F/B	15-20dB
5.	Radiating Efficiency	80-85W
6.	E-Field (1m)	9.5V/m
7.	H-Field (1m)	0.025 A/m
8.	E-Field (0.1m)	95-300 V/m
9.	H-Field (0.1m)	0.25-0.8 A/m

5. Conclusion

The research details the design and analysis of a compact SIW-based slot antenna for high-frequency microwaves. Fabricated on a Rogers 5880 substrate, the SIW cavity utilizes metallic vias for wave confinement. A longitudinal slot on the top plane facilitates efficient radiation. With dimensions of 17 mm x 8 mm, the antenna achieves a low profile. The proposed design demonstrates directional radiation and high efficiency. These characteristics position the SIW slot antenna as a potential solution for various wireless and RF applications.

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