EAI Endorsed Transactions
on Scalable Information Systems
Research Article **EAI.EU**

Design and Simulation of Quasi-microstrip Yagi Antenna in Railway Mobile Communication

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Abstract

PROBLEM STATEMENT: The performance and size constraints of the current railway mobile communication systems force the development of more effective communication methods.

OBJECTIVES: This study aims to build a quasi-microstrip Yagi antenna with a 900MHz centre frequency that minimizes the antenna's physical dimensions and improves communication capabilities between trains.

METHODS: HFSS simulation was used during the design phase to optimize the antenna's characteristics, which included bending the active oscillator to increase gain. Important performance indicators were assessed, including voltage standing wave ratio (VSWR), bandwidth, and return loss.

RESULTS: The optimized antenna produced a VSWR of less than 2, a maximum gain of 8.35dB, a bandwidth of 105MHz (spanning from 845MHz to 950MHz), and a return loss of -19.49dB at the centre frequency. According to these results, the antenna satisfies the operating criteria for railway mobile communication.

CONCLUSION: The quasi-microstrip Yagi antenna proves useful in engineering applications since it not only meets the communication requirements of railway systems but also shrinks considerably in size compared to conventional Yagi antennas.

Keywords: microstrip antenna; Yagi antenna; HFSS simulation; return loss; gain

Received on 22 08 2024, accepted on 09 11 2024, published on 16 01 2025

doi: 10.4108/eetsis.7029

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1. Introduction

The communication system between trains is a very important part of the train system. There are several kinds of antennas for the mobile terminal of the traditional inter-train indirect communication system: overhead disc antenna, overhead antenna and overhead pole vertical ground vibrator antenna [1]. For inter-train communication, the antennas in mobile terminals offer benefits, including clearer reception, enhanced signal coverage, and unobstructed line-of-sight. Because of their accessibility and separation from the train environment, they reduce interference from electrical devices and terrestrial sources, making maintenance easier. At the same time, the communication antenna between trains in the tunnel still uses coaxial leaky cables for signal coverage. To reduce project investment and maintenance difficulties, a new tunnel antenna scheme has been tried to replace the original leaky cable communication [2]. The tunnel antenna scheme improves signal coverage and minimizes dead spots in tunnel environments by optimizing antenna design, repeaters, MIMO technology, frequency selection, beamforming, and robust modulation techniques. This improves communication reliability and addresses environmental interferences and signal weakening. Enhancing safety, meeting specific needs, guaranteeing better connectivity, adjusting to high-speed situations, supporting more bandwidth for passenger data, and integrating with contemporary technologies like IoT and real-time tracking depends on improved antenna designs in railway mobile communication. Reducing maintenance requirements and interference also lowers operating expenses thanks to these developments. We can use an enhanced antenna in the tunnel to replace the coaxial leaky cable for communication coverage. Regarding signal quality and consistency, overhead antennas—especially those made for tunnel environments—outperform coaxial wires, which can have inconsistent coverage and deteriorate with age. Additionally, they offer more consistent, wider coverage, which minimizes dead zones in coaxial cable networks. Yagi antennas require less care than leaky cables but must be regularly checked for alignment and physical integrity. They are simpler to repair because of their exterior mounting. Because coaxial faulty wires are more prone to deterioration, moisture intrusion, and persistent leaking, they require more upkeep. The improved antenna is generally directional, which is necessary to match electromagnetic wave propagation characteristics in the tunnel, concentrate the direction, and cover a long distance [3].

Because of the limited space on the top of the train and the high speed of the train, the antenna arranged on the top of the locomotive not only cannot be too high but also must have a certain mechanical strength; at the same time, the occupied area cannot be too large. The antenna type and specifications used for rail systems must align with operating frequencies and environmental constraints. To maximize line-of-sight and prevent obstacles, antenna installation aboard trains must be done strategically, particularly in high-speed, heavily packed rail settings. Therefore, the Yagi antenna was chosen in the paper [1].

Yagi antenna, also known as a directional antenna, has the advantages of simple structure and strong directivity. A flexible and directing instrument, the Yagi antenna ensures precision and efficiency in various applications, including emergency communications, animal monitoring, amateur radio, long-range Wi-Fi networks, radio astronomy, and the study of astronomical frequencies. It is widely used in various wireless communication systems [4,5,6]. However, the disadvantages of the Yagi antenna are also obvious, such as its large size and narrow bandwidth. A quasi-microstrip Yagi antenna uses miniaturization techniques to minimize performance, save space, and reduce size. Because of its flat or planar design, which saves space, and materials with greater dielectric constants and lower resonant frequency, smaller antenna sizes are possible. At the same time, due to the large size of the Yagi antenna, it is difficult to conform with other carriers and cannot be applied in tunnels [3]. Therefore, this paper proposes a new scheme based on the paper [1], a quasi-microstrip Yagi antenna for inter-train communication. Planar antennas' cheap production and maintenance costs make them direct, small, and economical for train applications. In contrast to more durable conventional designs, they might not provide enough bandwidth for wide frequency coverage and might be more vulnerable to environmental deterioration.

Microstrip antenna[e] [7,8] have been widely used in satellite communication, radar, remote sensing, environmental testing, portable wireless equipment and other fields because of their small size, lightweight, small profile height, and conformal with the surface of missiles, satellites and other space vehicles. The dielectric constant and loss tangent of substrate materials like FR4 or Rogers impacts the performance of microstrip antennas. Minimal variations in antenna dimensions are guaranteed via precision production, essential for upholding performance criteria, particularly at higher frequencies.

2. Antenna design

The performance of the Yagi antenna is maximized by carefully choosing factors like feed impedance, length, boom length, element number, spacing, and material. These factors affect gain, directivity, bandwidth, and impedance matching to ensure efficient signal reception and transmission. The antenna's affordability and robustness are improved by customization, which qualifies it for a range of radio frequency applications. The Yagi antenna design, especially in the quasi-microstrip configuration, is advantageous for railway communication systems because of its small and flat construction, high gain and directional radiation, and enhanced gain and directivity due to meticulous guiding oscillator selection.

2.1. Index Design

According to Article II of the *Implementation Rules for the Use of Railway Radio Frequency License*, the National Railway Administration is entrusted by the Ministry of Industry and Information Technology to implement the licensed 400MHz, 450MHz, 800MHz, and 900MHz frequency bands are the radio frequencies, which railway transport enterprises can use. This paper selects the 900MHz frequency band as the communication frequency band between trains (uplink band: 885MHz ~ 890 MHz; downlink band: 930 MHz ~ 935 MHz). Extended railway routes benefit greatly from the decreased path loss and longer communication range of the 900 MHz frequency band. Additionally, it improves the connection in intricate railway situations by enabling greater penetration through barriers like buildings and bridges. It could, however, deliver slower data speeds than higher frequency bands and become congested owing to interference problems.

This design requires that the gain is greater than 8dB, the VSWR (Voltage Standing Wave Ratio) in-band is less than 2, and good radiation directivity is needed.

2.2. Antenna structure

Yagi antennas are directional arrays of directors, reflectors, and driving elements used for railway mobile communications. It improves forward gain and directivity through matched elements, influencing radiation pattern and impedance. Its resilience and simplicity make it simple to install and maintain even in the most difficult railway conditions. The Yagi antenna consists of an active oscillator, some guide oscillators, and a reflect oscillator; its structure is shown in Figure 1. The antenna radiation pattern can be improved and size reduced by the active oscillator's bend. The choice of dielectric substrate is critical for balancing performance and size since it affects bandwidth, efficiency, and antenna size.

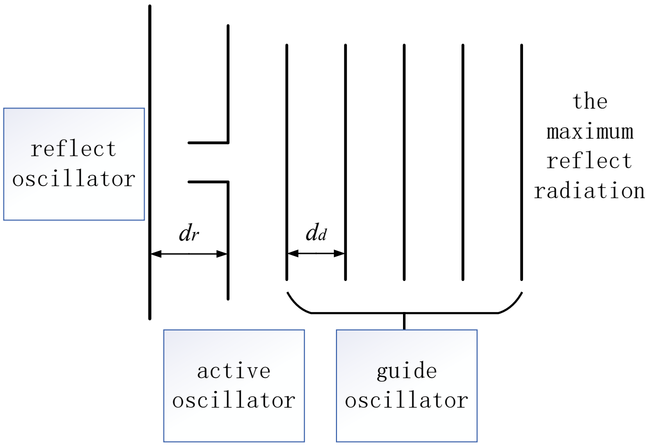


Figure 1. Yagi antenna structure diagram

The quasi-microstrip Yagi antenna's design specifications for railway communication systems were carefully chosen to provide the best possible radiation efficiency and directivity. Adjusting the active and guide oscillators to match the feeding network and maximize impedance bandwidth at a spacing of around 0.2λ allowed for balancing impedance matching, gain, and front-to-back ratio. Theoretically, the length of the reflect oscillator is: The size of the active oscillator is: The length of the guide oscillator is: The distance between the oscillator and the active oscillator is: The distance between the active oscillator and the guide oscillator is:

2.3. Parameter calculation

This paper selects the FR4 epoxy resin board with a relative dielectric constant of 4.4, loss tangent angle of 0.02, and thickness of 0.8mm as the dielectric substrate. The dielectric substrate selection greatly impacts antenna performance, which affects environmental stability, size, efficiency, and bandwidth. While decreasing antenna size, higher dielectric constants result in higher losses. In railway applications, low-loss tangent substrates enhance mechanical resilience and thermal stability, reduce power loss, and offer a wider bandwidth for multi-frequency train communications.

In this paper, the central frequency of the antenna is 900MHz. The study for railway communication selected the 900 MHz frequency band because it is practically relevant, provides a balance between penetration ability, bandwidth, and propagation range, ensures dependable propagation over long distances and improved connectivity through obstacles like infrastructure and train carriages, and is compatible with current systems. If the electromagnetic wave propagates in free space, the corresponding wavelength is 333.3mm. If the electromagnetic wave propagates in a medium filled with FR4 material, the parameters of the quasi-microstrip antenna can be calculated using the following formulas. The quasi-microstrip Yagi antenna is a low-profile, small-diameter mobile communication option for high-speed trains. It requires minimal maintenance, minimizes interference, supports several frequency bands, and maintains strong connections. It may be easily incorporated into current systems to improve service quality and communication dependability. A quasi-microstrip antenna employing FR4 material may be more reliable and perform better by considering temperature, substrate thickness, loss tangent, manufacturing tolerances, size limitations, cost, and dielectric constant fluctuation. To assess frequency changes, use tuning features and cautious estimations.

$$W = \frac{c}{f\sqrt{2(\varepsilon_r + 1)}} \quad (1)$$

According to formula (1), we can calculate the patch widths W of the active oscillator and guide oscillators. Where c is the speed of light in free space, f is the antenna's resonant frequency and ε_r is the relative dielectric constant of the antenna. The choice of materials, notably the dielectric substrate, was critical for the antenna's performance. A low-loss tangent (δ) substrate was selected for its mechanical durability and resilience to the dynamic train environment. At the same time, a moderate dielectric constant (εr) was chosen to balance efficiency and miniaturization.

$$\varepsilon_e = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left(1 + 10\frac{h}{W}\right)^{-\frac{1}{2}} \quad (2)$$

According to formula (2), we can calculate the equivalent dielectric constant ε_e of the antenna. Where h is the thickness of the dielectric substrate.

$$\lambda_g = \frac{c}{f_0\sqrt{\varepsilon_e}} \quad (3)$$

According to formula (3), we can calculate the working wavelength λ_g of an electromagnetic wave transmitted in the medium. Where f_0 is the working frequency of the antenna.

From formulas (1), (2), and (3), we can calculate the patch width W is 11.1mm, the relative dielectric constant of the antenna ε_r is 3.97, and the working wavelength of an electromagnetic wave with an operating frequency of 900MHz propagating in the medium is 167.4mm.

The actual operating wavelength of the antenna should be between 333.3mm and 167.4mm because the antenna's propagation environment contains both medium and free space. Therefore, we take the mean value of 250mm of the two as the operating wavelength λ of the antenna.

3. Antenna modeling and simulation

3.1. Selection of modeling parameters

Yagi antenna is a mutually coupled antenna. The choice of the length of each oscillator and the spacing between each oscillator greatly influence the antenna pattern and other performance. Generally, the reflect oscillator L1 length should not be less than 0.5λ. The size of the active oscillator L2 is generally about 0.45λ. The length of the guide oscillator L3 is generally about 0.4λ.

In practice, the antenna pattern and the actual size of the oscillators should be adjusted according to the above range combined with the simulation results.

According to general experience and the design principle of the Yagi antenna, we choose the length of the active oscillator to be 0.5λ, the lengths of the guide oscillators to be 10% shorter than 1/2 of the wavelength, that is, 0.45λ, and the size of the reflect oscillator is 0.55λ. The distance between the reflect oscillator and the active oscillator is 0.22λ, the distance between the active oscillator and the guide oscillator is 0.22λ, and the distance between each guide oscillator is 0.22λ. The guide oscillator length of the Yagi antenna can be designed to be equal or non-equal. In this paper, equal length is selected.

3.2. Modeling model

In this paper, we design the Yagi antenna, which consists of three parts: an active oscillator (a printed dipole antenna), six guide oscillators, and a reflect oscillator. The active, directing, and reflector elements are the three main parts of the Yagi antenna. After receiving signals, the driven element causes the other components' currents to flow. The director elements increase gain and directivity towards the desired direction by forwarding the antenna's energy. The reflector increases the forward gain and front-to-back ratio by reflecting backwards waves. Thanks to these parts, the Yagi antenna is extremely efficient and directed. In railway applications, in particular, the design process takes durability, thermal stability, and simplicity of maintenance and repair into account to provide resilience to vibrations, large temperature fluctuations, and prompt repairs. All structures are on the same side of the dielectric substrate. A microstrip line feeds a 2mm gap in the middle of the dipole antenna. Smart antenna technology, material selection, geometry optimization, sophisticated matching techniques, environmental adaption design, frequency agility, simulation, and creative feeding approaches are some suggested methods for enhancing antenna performance. The antenna model is shown in Figure 2.

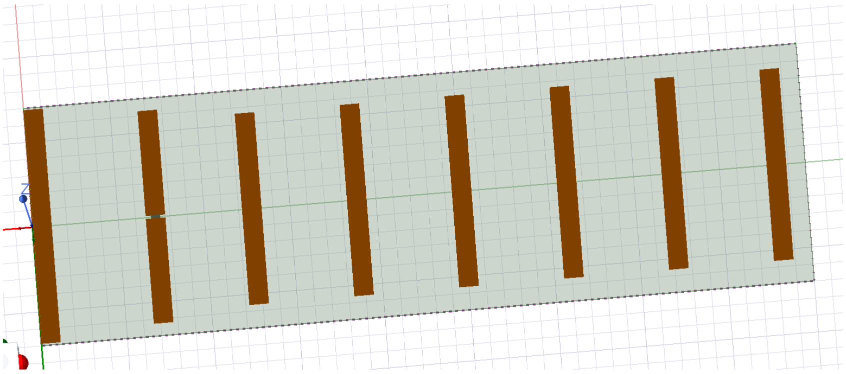


Figure 2. Modeling model diagram

The initial parameter values of the antenna structure are shown in Table 1.

Table 1. Initial parameter value of antenna structure (unit: mm)

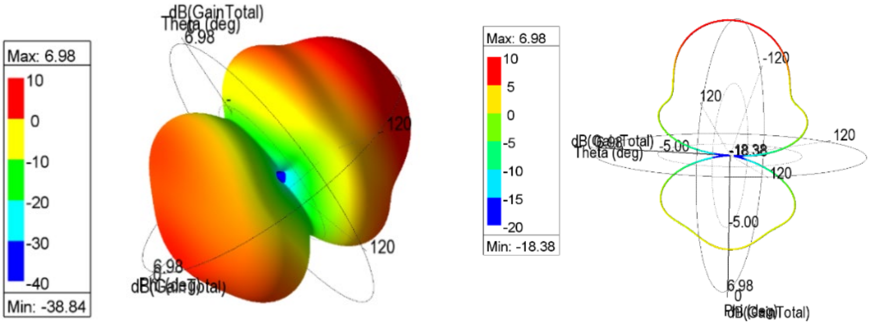
Parameter meaning	Parameter	Value
the thickness of the dielectric slab	H	0.8
width of the dielectric slab	W	140
length of dielectric slab	L	450
width of oscillators	W1	11.1
length of active oscillator	L1	125
length of reflect oscillator	L2	137.5
length of guide oscillator	L3	112.5
distance between the reflect oscillator and the active oscillator	dr	55
distance between the active oscillator and the guide oscillator	dd	55

3.3. Performance simulation and analysis

Direction pattern, return loss (S11) and VSWR (Voltage Standing Wave Ratio) are the main parameters to evaluate the performance of an antenna. Voltage Standing Wave Ratio (VSWR), return loss, and directional pattern are used to assess antenna performance. The directional pattern shows the energy distribution and the power reflected by the antenna is measured by return loss. A VSWR that is almost 1:1 ensures that there is little power reflection. These factors establish an antenna's efficiency, directivity, and power consumption for the planned application. Resistance, reactance, corrosion, and impedance matching may all be adversely affected by environmental conditions such as temperature changes, humidity, precipitation, mechanical stress, and vibrations. These issues are especially important regarding antenna performance in railway applications.

S-parameters are measured using HFSS to evaluate the antenna's efficiency and bandwidth by measuring its transmission and reflection properties. The simulator ensures that the antenna's impedance matches the transmission line or system to minimize power losses. For the antenna modelled according to the above theory, we can get its directional pattern by HFSS simulation, which is shown in Figure 3.

Using the finite element approach, HFSS is a simulation tool for designing and analyzing high-frequency electrical components. In addition to properly modelling real-world circumstances, it solves Maxwell's equations and creates 3D representations. Offering insights before the construction of prototypes improves performance in making electronic components.



(a) 3D directional pattern (b) E plane directional pattern

Figure 3. Antenna directional pattern

From the directional pattern, we can see that the rear lobe of the antenna is too large, and the gain is only 6.98dB, which does not meet the requirement that the gain be greater than 8 dB.

The return loss S11 of this model is shown in Figure 4.

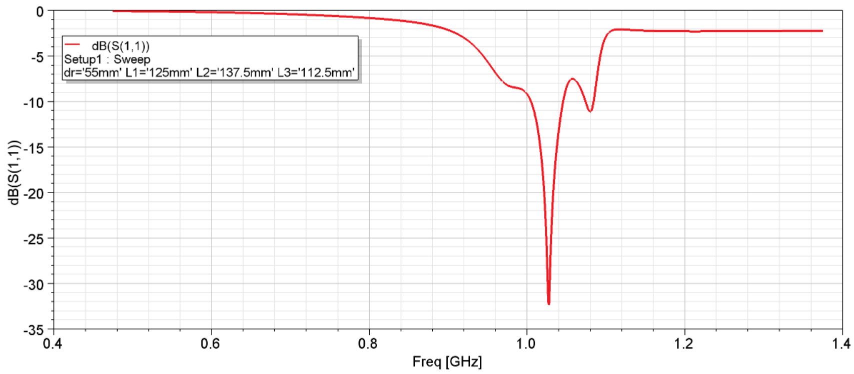


Figure 4. Return loss S11

From Figure 4, we can see that the antenna's resonant point is not 0.9GHz, and the operating frequency band does not include the operating range of 885MHz to 935MHz (uplink band: 885MHz to 890 MHz, downlink band: 930MHz to 935MHz).

The VSWR of this model is shown in Figure 5.

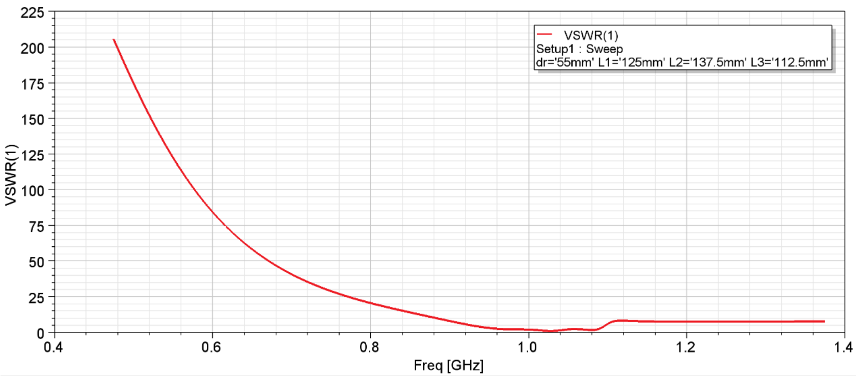


Figure 5. VSWR

Figure 5 shows that the antenna's VAWR in the operating frequency band is much greater than 2.

We found that all antenna indexes modelled according to the theory could not reach the standard after simulation.

Hence, we need to optimize the model so that each performance can meet the requirements of railway mobile communication. Antenna model evaluation for railway mobile communication addresses frequency range, bandwidth, signal gain, durability, size, interference handling, regulatory compliance, and efficiency. Covering frequencies, delivering gain, overcoming environmental obstacles, adhering to safety regulations, and guaranteeing operational costs are the factors that affect performance. The model satisfies railway communication performance standards by covering particular frequencies, guaranteeing resilience against environmental difficulties, guaranteeing unobstructed communication over railway tracks, and optimizing VSWR and Impedance Matching to reduce power losses and preserve signal integrity despite possible ecological problems.

4. Antenna Optimization

Optimizing each parameter in the model can optimize the antenna pattern, return loss (-S11), and voltage standing wave ratio. The optimized model is shown in Figure 6. Numerous obstacles had to be overcome in the antenna design and optimization process, including coupling reduction, environmental robustness, and bandwidth optimization. Iterative simulations were utilized to modify the element width and dielectric substrate characteristics to accommodate different communication needs in train settings.

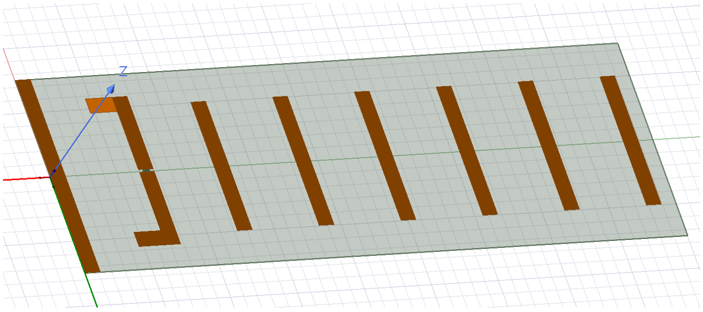


Figure 6. Optimization model

To increase the radiation intensity, bent structures are added at both ends of the dipole antenna, and the bent structures on both sides are symmetrical. The bent structures are shown in Figure 7.

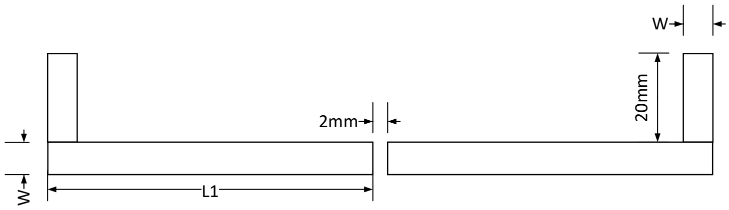


Figure 7. Bent structures

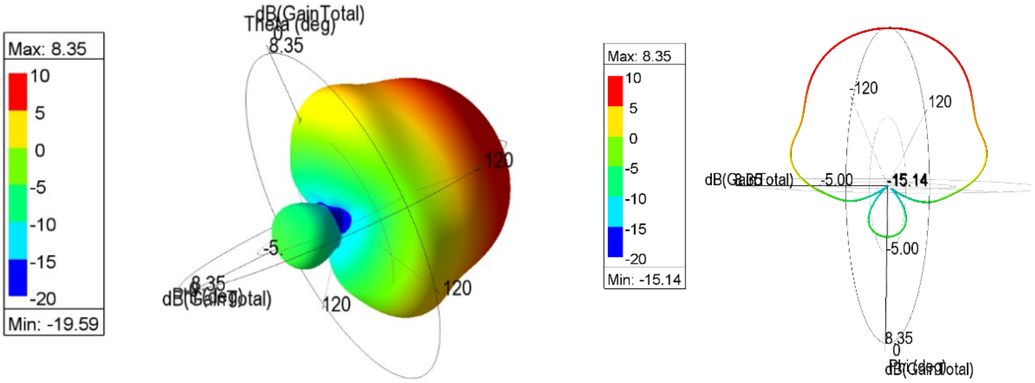
The optimized parameters are shown in Table 2.

Table 2. Optimization Values of Antenna Structural Parameters (Unit: mm)

Parameter meaning	Parameter	Value
the thickness of the dielectric slab	H	0.8
width of the dielectric slab	W	150
length of dielectric slab	L	450
width of oscillators	W1	11.1
length of active oscillator	L1	115
length of reflect oscillator	L2	150

length of guide oscillator	L3	100
distance between the reflect oscillator and the active oscillator	dr	55
distance between the active oscillator and the guide oscillator	dd	55

After model improvement and parameter optimization, the direction diagram of the model is shown in Figure 8.



(a) 3D directional diagram (b) E-plane directional diagram

Figure 8. Directional diagram of the improvement model

Figure 8 shows that after model optimization, the back lobe of the antenna is significantly reduced, and the gain reaches 8.35dB, which meets the requirement of a gain greater than 8dB in railway mobile communication.

The performance of the quasi-microstrip Yagi antenna was evaluated by comparing its initial and optimized versions. The optimized model accomplished improved impedance matching, less signal reflection, and a return loss of -19.49dB at 900MHz, extending bandwidth to 105MHz. It also guaranteed minimum signal loss with a voltage standing wave ratio of less than 2. The comparison chart of the return loss between the initial and optimized models is shown in Figure 9.

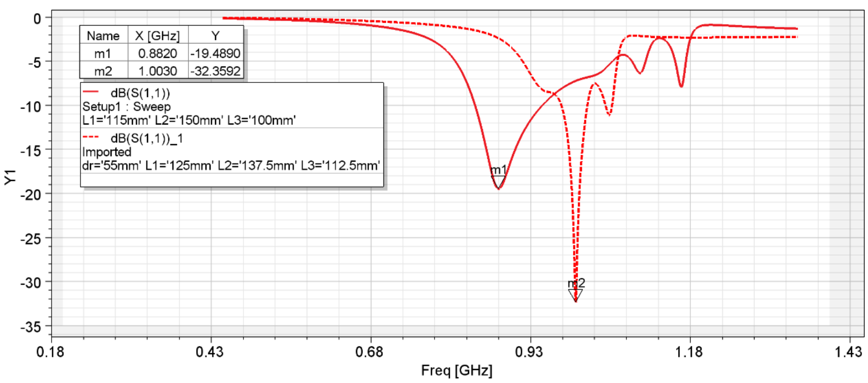


Figure 9. The comparison of the return loss between the initial model and the optimized model

Figure 9 shows that the optimized model's resonance point and bandwidth meet the requirements.

The comparison of VSWR between the initial model and the optimized model is shown in Figure 10.

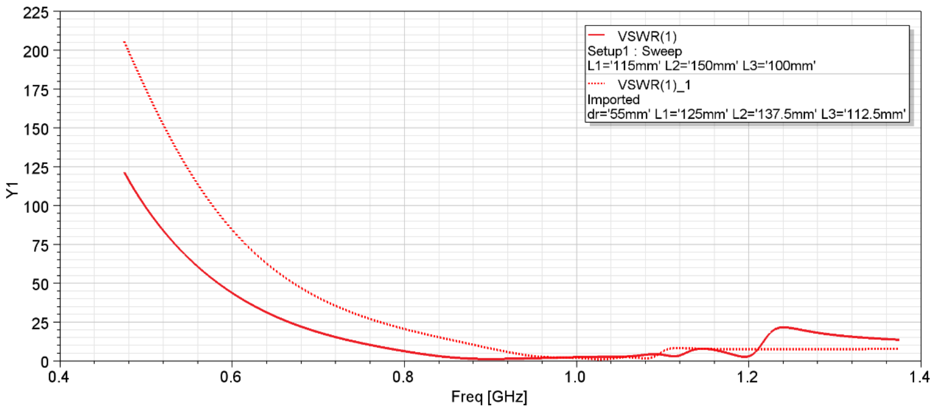


Figure 10. Comparison of VSWR between the initial model and the optimized model

Figure 10 shows that the optimized model's VSWR is less than 2 within the bandwidth range, which meets the requirements.

5. Conclusion

The study effectively built and optimized the quasi-microstrip Yagi antenna for train mobile communication, yielding notable performance metrics. The effective frequency range for this antenna is 105 MHz or 845 MHz to 950 MHz. It has a return loss of -19.49dB at the centre frequency 900MHz, demonstrating effective power transmission with little reflection. Signal strength and communication dependability are improved by the 8.35dB maximum gain that was measured. Moreover, excellent impedance matching is ensured across the operating frequency range by maintaining the voltage standing wave ratio (VSWR) at less than 2. Our results validate that the quasi-microstrip Yagi antenna satisfies the unique demands of railway mobile communication while providing a small form factor useful for real-world engineering uses.

Data Sharing Agreement

The datasets used and/or analyzed during the current st udy are available from the corresponding author on reasonab le request.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) received no financial support for the rese arch.

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