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4-to-1 Microwave Power Combiner/Amplifier for Ka-Band Frequency Using Rectangular Waveguide with Cylindrical Post Tuning Technique for Impedance Matching

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Abstract: Combining amplifier outputs into one transmission line is typical for microwave applications. The study offers a 4:1 WR28 waveguide power combiner for Ka-band frequency simulated in CST Studio Suite. Current Ka-band 4-way power combiners use microstrip-to-waveguide transitions based on microstrip patches. This design uses a multilayer PCB. The model was also simulated using 3D full-wave electromagnetic field software. A 4:1 spatial combiner using WR28 waveguide for Ka-band microwave combining is presented. The 32–38 GHz power combiner interfaces with Ka-band equipment. Through thorough electromagnetic simulation and optimisation, the design achieves a 0.5 dB insertion loss, a 15–35 dB isolation range, and a 13–50 dB return loss. Combiner simulations used high-frequency issue types with silver as the material. The VSWR is below -10 dB, showing low reflection and making it perfect for wave combining. Experimental validation shows that the power combiner is suitable for Ka-band systems. This combiner meets or exceeds performance standards, making it a viable option for Ka-band microwave applications. The design's effective execution demonstrates its potential to enhance Ka-band system performance, thereby advancing telecommunications and related fields. The power combiner meets Ka-band application requirements thanks to electromagnetic simulation and optimisation. The combiner is cost-effective for Ka-band systems because it ensures great performance and resource efficiency.

Keywords: Ka-Band Frequency; Printed Circuit Board; 3D Full-Wave Electromagnetic Field; Voltage Standing Wave Ratio; Computer Simulation Technology; Cost-Effective Solution; Rigorous Electromagnetic Simulation.

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1. Introduction

A 4-to-1 power combiner is a passive microwave device that combines four input signals into a single, common output signal. Each input signal typically carries the same amount of power. By combining multiple input signals, a power combiner effectively increases the total power available at its output port. The primary objective of this research is to develop a power combiner that integrates a microstrip-to-waveguide transition while minimising insertion loss and maximising efficiency. The design of the four-way power combiner is based on integrating a microstrip-to-waveguide transition. The structure consists of two patches with two microstrip accesses each, housed within a rectangular cavity formed by a machined adapter serving as an interface to a standard WR28 waveguide opening. The model was designed using 3D full-wave electromagnetic field simulation software.

Measurement results of the four-way power combiner are presented, focusing on insertion loss, return loss, isolation, and transmission coefficients. Operating at 30 GHz, the existing combiner features an isolation range of 14 to 8 dB, a return loss of 20 dB, and an insertion loss of 0.54 dB. The proposed 4-way power combining model utilises transmission line theory, combining Ka-band frequency microwave signals employing the WR28 TE10 mode in a rectangular waveguide configuration. The presented model achieves better results of S-parameters and optimal VSWR. This report presents a detailed analysis of power combining from four sources of equal amplitude and phase, designed for use at higher frequencies in the Ka-band, ranging from 32 to 38 GHz, utilising a WR28 rectangular waveguide. The design and analysis of this power combiner have been presented and designed using the electromagnetic simulation platform, Computer Simulation Technology (CST) Studio Suite. Figure 1 shows a fabricated 4-way waveguide power combiner.

Figure 1: A fabricated 4:1 waveguide combiner

2. Literature survey

A full Ka-band waveguide-based spatial power-combining amplifier, based on E-plane anti-phase probes, was designed to provide less insertion loss, thereby increasing the combining efficiency. It is a solid-state power amplifier, a key component for modern radar and communication systems [3]. The insertion loss achieved using the magic-tee circuit was significant to our paper. 4-way combiners using embedded microstrip-to-waveguide transitions can be implemented primarily to achieve a compact and low-cost solution [2]. Rectangular waveguides play a crucial role in power combining and transition techniques, enabling a broadband response [1]. Before combining the input signals, impedance matching between the input device and the waveguide must be achieved, which can be accomplished efficiently by adopting coaxial-to-waveguide transition techniques [4]. Impedance matching is a crucial concept in the design and operation of guided wave structures, such as waveguides, microstrip lines, and other transmission lines used in high-frequency and microwave applications [7]. Wilkinson power dividers/combiners and microstrip patch antennas are effective for impedance matching and broadband solutions due to their inherent design features that ensure matched impedance, high isolation, low insertion loss, and a wide bandwidth [9].

Incorporation of a fully optimised Magic-Tee is crucial for power combining in microwave and RF networks [10]. The junction is widely used due to its outstanding ease of design and fabrication, which can be achieved using any metal, as well as its low-loss output and high capacity. In the field of RF and microwave systems, power combiners play a crucial role in combining the output power from multiple sources into a single output of a higher level of power. Microwave power combining and impedance matching techniques are evolving more than ever before, driven by the increasing demand for high-frequency communication and radar systems that deliver optimal performance [11]. Power combiners have emerged as a crucial component for merging multiple input signals into a single output channel, ensuring impedance matching and minimising losses [8]; [12]; [13]. Various fundamental design models can achieve these objectives, including radial and spatial power combiners, coaxial-to-waveguide transitions, and coaxial waveguide couplers [5]; [6]. The significance of achieving impedance matching, low-loss output, and optimal VSWR and S-parameters is explained in this introduction. The power combiners are used as an amplifier. There are power combiners that combine the powers of different frequencies and amplitudes, as well as those that combine the powers of equal frequencies and phases. Combiners may have n number of inputs.

This research involves manipulating the waveguide to modify its passive properties, including resistance, inductance, and capacitance. Key parameters considered during the design of the combiners were the losses due to transmission, insertion, and reflection. Factors considered included the physical dimensions of the rectangular waveguide to ensure efficient power combining while minimising impedance mismatches and transmission losses. Additionally, factors such as isolation between input ports and the overall insertion loss were taken into account during the design process.

2.1. Waveguides

A waveguide is another form of transmission line. It consists of a hollow metal or dielectric tube or channel that confines and directs electromagnetic waves along its length, preventing their propagation in other directions. Waveguides provide minimal power loss and extremely low attenuation values. Microwave energy encounters lower losses when transmitted through waveguides compared to coaxial cables. Figure 2 shows the pictorial representation of the different types of waveguides.

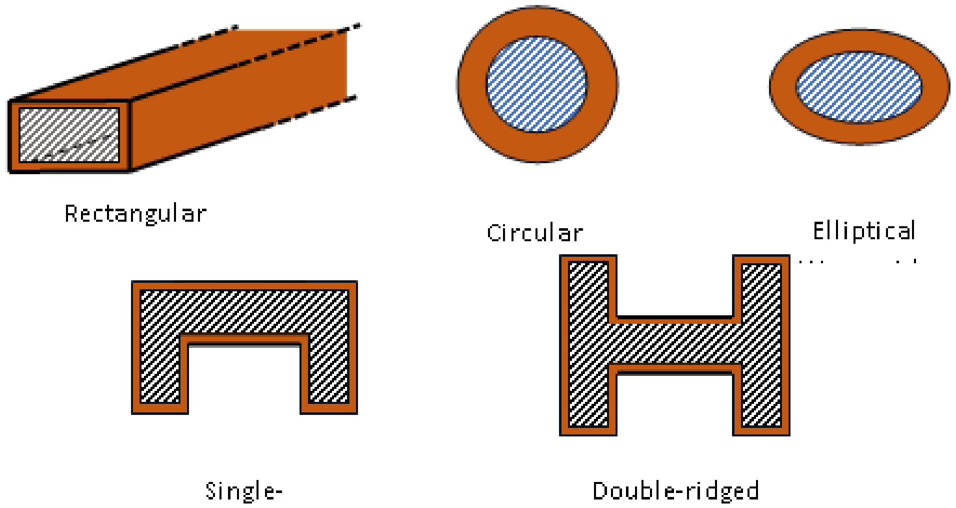

Figure 2: Types of waveguides

Rectangular waveguides are commonly used in microwave and RF applications, in various communication and radar systems. They are popular for routing electromagnetic waves due to their simple structure and ease of fabrication. The rectangular shape of the waveguide allows it to support a single dominant mode of propagation, TE10. One of the key advantages of these waveguides is their high-power handling capabilities with minimal losses, which make them suitable for high-frequency applications. Additionally, the reason they are widely used for carrying signals over long distances without significant distortion is their well-defined structure, which facilitates low dispersion.

2.2. Propagation Modes in a Rectangular Waveguide

The mode propagation in rectangular waveguides is a fundamental concept that governs the behaviour of electromagnetic waves within the waveguide structure. The dominant mode of propagation is determined by the dimensions of the waveguide and the frequency of the input signal. Understanding the mode propagation is essential for optimising the performance of rectangular waveguides in different applications. The following are the modes in which waves propagate within a waveguide:

- **TE:** Transverse Electric
- **TM:** Transverse Magnetic
- **TEM:** Transverse Electric and Magnetic

2.2.1. TE Mode

As seen below in Figure 3, in TE of waves, the electric field is perpendicular to the direction of wave propagation. Meanwhile, the magnetic field can have components in both the transverse and longitudinal directions. TE modes do not have electric field components along the direction of propagation.

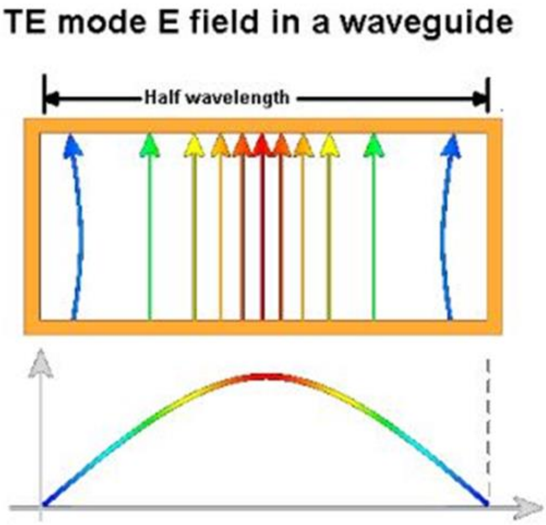

Figure 3: TE mode

TE10 is the dominant mode that can propagate through a rectangular waveguide. The indices "1" and "0" signify that there is one half-wave variation across the width of the waveguide and no variations along the height. The various modes of TE are illustrated in Figure 4 below. The Electric field (E) oscillates perpendicular to the direction of propagation. The magnetic field (H) is directed perpendicular to both the electric field and the direction of propagation.

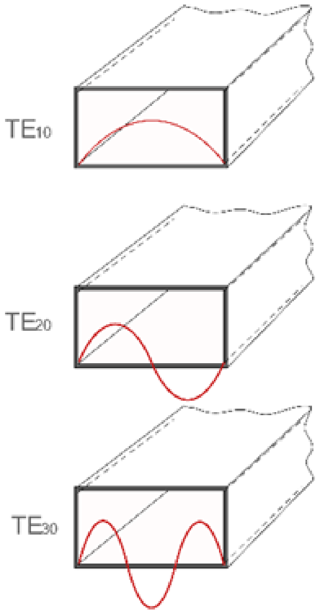

Figure 4: Different modes of TE

2.2.2. TM Mode

In TM mode, the magnetic field is transverse to the direction of wave propagation. Meanwhile, the electric field can have components in both the transverse and longitudinal directions. Figure 5 below shows the given representation of TM Mode. TM modes do not have magnetic field components along the direction of propagation. Just like the TE mode, it can be transmitted using rectangular waveguides. The TM mode of wave propagation is distinguished by electric field vectors that are perpendicular to the path of wave propagation. In contrast, magnetic field vectors are in the plane of propagation. In other words, electromagnetic waves in TM mode have transverse electric and magnetic fields, with no component of the electric field parallel to the direction of propagation. This unique configuration distinguishes TM mode from other modes, such as Transverse Electric (TE) and Hybrid, which have differing field orientations and propagation properties.

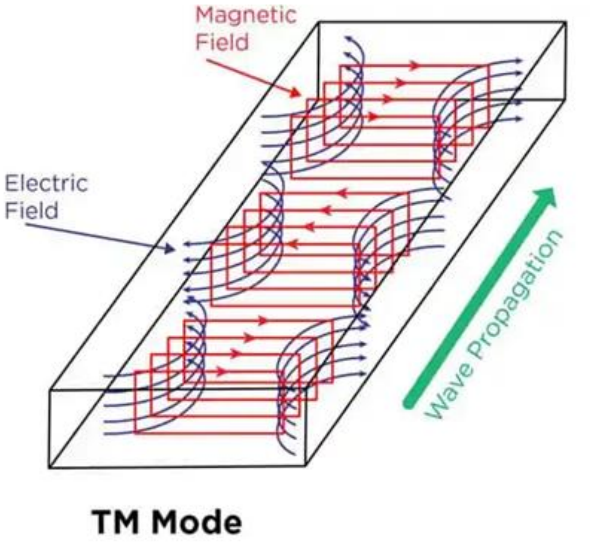

Figure 5: TM mode

2.2.3. TEM Mode

In the TEM mode, both the electric and magnetic fields extend across the waveguide perpendicular to the direction of wave propagation, lacking any field components along the propagation direction. The TEM is different and requires solid metal conductors on both sides to travel within. Figure 6 shows the TEM Mode waveform in a rectangular waveguide.

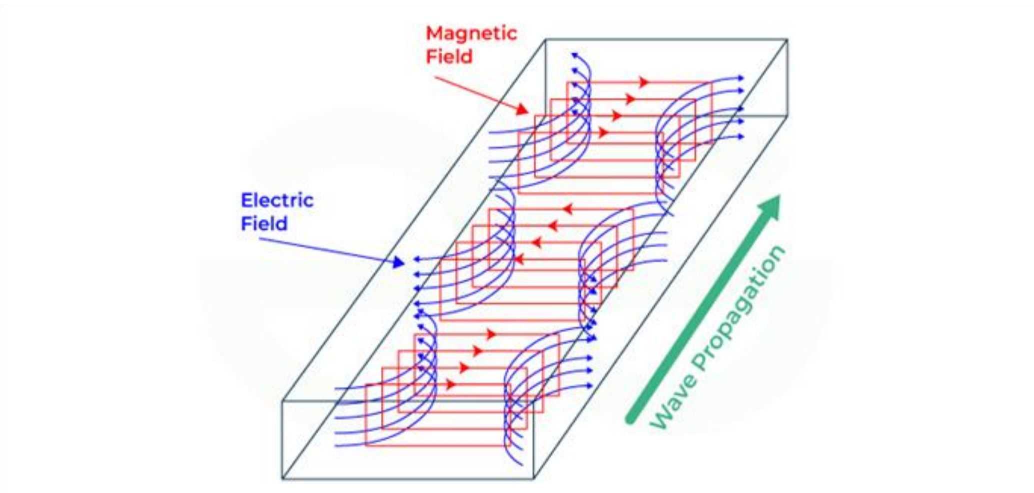

Figure 6: TEM mode

A TEM mode cannot exist in a waveguide, as it would require an axial current to pass through some central conductor to give rise to a transverse magnetic field, and in the absence of any such conductor, this mode cannot exist. Thus, such a mode can travel in a coaxial waveguide. Each mode has its unique characteristics and applications, and the specific mode that predominates in a given waveguide depends on factors such as its geometry, boundary conditions, and frequency of operation.

2.2.4. WR28

The WR28 waveguide is used to make this power combiner. This is because the inner dimensions of this waveguide are height and width, which are 3.56mm and 7.11mm; and the wavelength of the waves belonging to the Ka-band is given by equations (1), (2), and (3).

$$\lambda = \frac{c}{\nu} \quad (1)$$

$$\lambda = \frac{3*10^8}{35*10^9} \quad (2)$$

$$\lambda = 8.5\text{mm} \quad (3)$$

Thus, WR51, WR42, WR34, and WR28 can be used to carry these frequencies. We use WR28 for this, as it is the one assigned for the wavelength of the higher-order frequencies in the Ka-band. WR28 is illustrated in Figure 7 below.

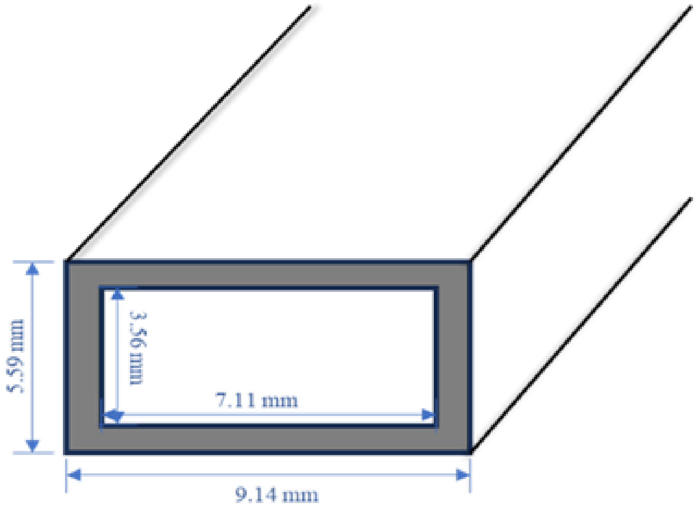

Figure 7: Rectangular waveguide and WR28

The length of these can be infinite, as the wavelength does not constrain them; however, we need to keep the length as small as possible, because we may have to deal with a heavier loss in transmission if the path it travels along is longer.

2.3. Impedance Matching

Impedance matching is a crucial aspect in waveguide transmissions as it ensures that maximum power transfer occurs between the source and load. Several techniques can be employed to achieve impedance matching in waveguide transmissions.

2.4. Step-Wise Impedance Matching

As shown in Figure 8, it is used to match the impedance between two components in an electrical circuit by gradually transitioning between different impedance values in discrete steps.

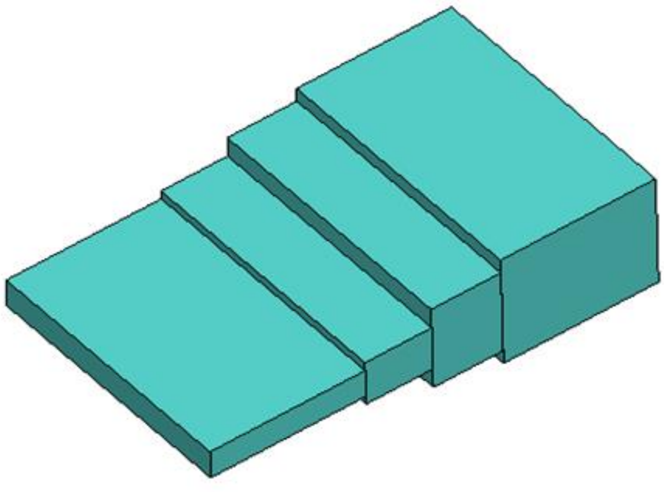

Figure 8: Step-wise impedance matching

This technique is often employed in transmission lines, waveguides, and other RF/microwave systems to minimise signal reflections and optimise power transfer.

2.5. Tapered Transitions

By gradually tapering the dimensions, the impedance of the waveguide can be adjusted to match that of the connected components, maximising power transfer efficiency and reducing signal loss.

Figure 9: Tapered impedance matching

Various waveguide applications, including antenna systems, microwave circuits, and radar systems, employ tapered transitions to optimise performance and minimise signal distortion. Tapered transitions, shown in Figure 9, gradually change the dimensions of the waveguide to ensure a smooth transition between different impedance levels. Moreover, tuning screws are placed to fine-tune the impedance matching at certain specific frequencies.

2.6. Cylindrical Post Tuning

This method involves inserting a cylindrical metallic post into the waveguide at specific locations to achieve the desired impedance matching, as shown in Figure 10. The primary objective of post-tuning is to adjust the impedance of the waveguide to match that of the load or another section of the waveguide, thereby minimising reflections and ensuring maximum power transfer. The post creates a localised change in the waveguide's impedance. This change can be used to cancel out the reactive component of an impedance mismatch. By adjusting the position (distance from the waveguide walls) and the height of the post, the exact reactance needed to match the impedance can be achieved.

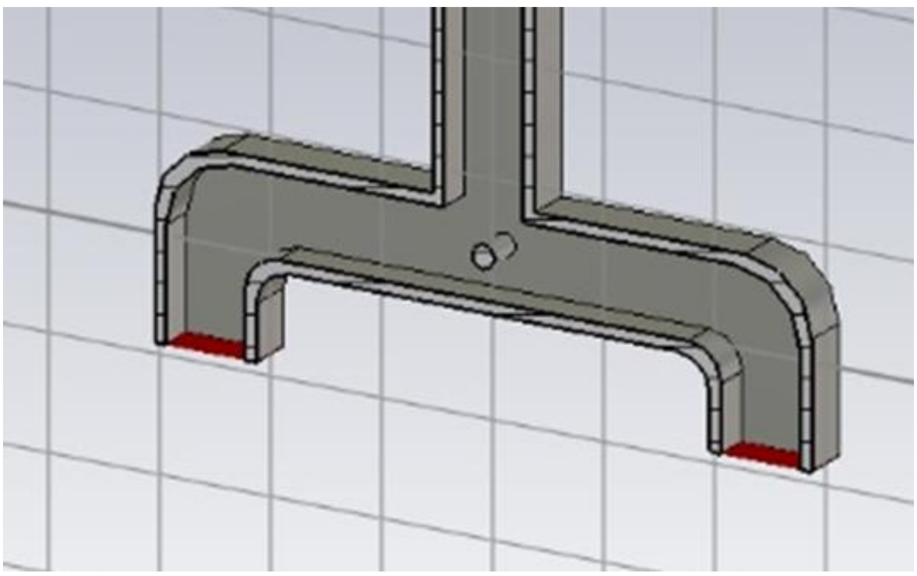

Figure 10: Cylindrical post-tuning

2.7. Magic Tee

A magic tee is a type of microwave waveguide component used in RF and microwave systems for combining, splitting, and routing signals. It consists of a four-port waveguide junction with specific internal dimensions that enable it to perform various functions, as shown in Figure 11. This is also called a Hybrid or 3dB coupler. To form an E-H Plane Tee junction, two simple waveguides, one parallel and the other series, are attached to a simple 2-port rectangular waveguide. The arms of rectangular waveguides form two ports, referred to as collinear ports, namely Port 1 and Port 2. Port 3 is designated as the H-Arm, Sum, or Parallel port. Port 4 is called the E-Arm, or Difference port, or Series port. To form an E-H Plane Tee junction, two simple waveguides, one parallel and the other series, are attached to a simple 2-port rectangular waveguide.

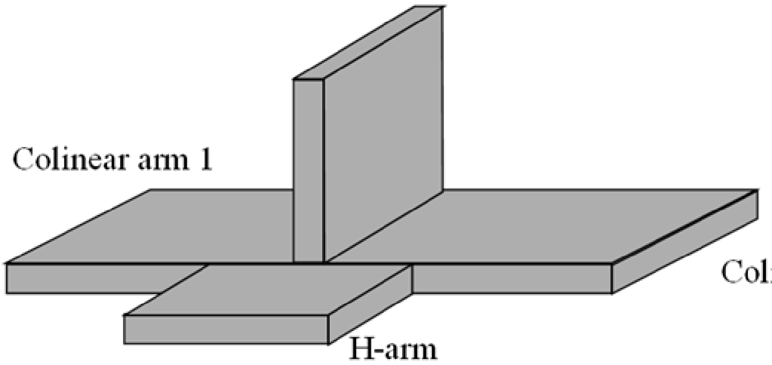

Figure 11: Magic tee

S-parameters of a Magic Tee can be obtained by using equation (4)

$$[S] = \begin{bmatrix} S_{11} & S_{12} & S_{13} & S_{14} \\ S_{21} & S_{22} & S_{23} & S_{24} \\ S_{31} & S_{32} & S_{33} & S_{34} \\ S_{41} & S_{42} & S_{43} & S_{44} \end{bmatrix} \tag{4}$$

Magic Tee as a Combiner: The primary function of a magic tee is the ability to split or combine microwave signals with specific phase relationships. When a signal is applied to one of the input ports (E or H port), the magic tee maintains phase coherence while dividing the input power between the two output ports (1 and 2 ports). Conversely, when signals are applied to the output ports, the magic tee combines these signals at the input port, ensuring minimal loss and optimal signal integrity.

Magic Tee as a Divider: Since the Magic Tee is based solely on the phase relationships between inputs from various ports, power division between input and output ports can be accomplished with ease. The phase relationships, as shown in Figure 11, determine whether the combined signals exhibit constructive or destructive interference, while the power division ensures a balanced distribution between the output ports.

3. Proposed Methodology

A 4-way power combiner operates based on the principle of wave superposition and transmission line theory. Each input signal travels through the interconnecting waveguide paths of the combiner. These waveguides are carefully designed to provide impedance matching and efficient signal combining while minimising losses. Figure 12 shows the structure of the proposed combiner model and the flow of the input microwave signals. Each input signal is fed into its respective waveguide port. For a 4-way combiner, there are four input ports. These input ports are typically rectangular waveguide apertures where the microwave signals are introduced into the waveguide structure. Once inside the waveguide, the microwave signals propagate along the waveguide's hollow metal structure. In the TE10 mode, the electric field is perpendicular to the direction of propagation, while the magnetic field is parallel to it. Inside the combiner, the waveguide structure forms a network of bends, tees, or directional couplers. This network is designed to distribute the incoming signals from the input ports and combine them efficiently.

As the signals travel through the waveguide network, they are divided and distributed to reach the output port. The dimensions and lengths of the waveguides are precisely designed to ensure that signals from different input ports arrive at the output port in phase. At the output port, the signals from all input ports are combined. If the signals are in phase, their electric fields add up constructively, resulting in increased amplitude (power) at the output port. The combining process is achieved through the proper design of the waveguide structure, ensuring that the signals combine efficiently. The combined signal is obtained at the output port of the combiner. This output port is connected to the load or the next stage of the system. The output signal carries the combined power of all input signals and is ready for further processing or transmission. Designing a 4-way power combiner requires careful consideration of multiple parameters to achieve the best performance and efficiency. Four-way power combiners have a wide range of applications in RF systems, including phased array antennas, distributed antenna systems (DAS), RF power amplifiers, and radar. These combiners offer effective signal combining, beamforming, and power distribution, which improve system performance and functionality. The 4-way power combiner is a crucial component in RF engineering, enabling the seamless integration of signals from multiple sources.

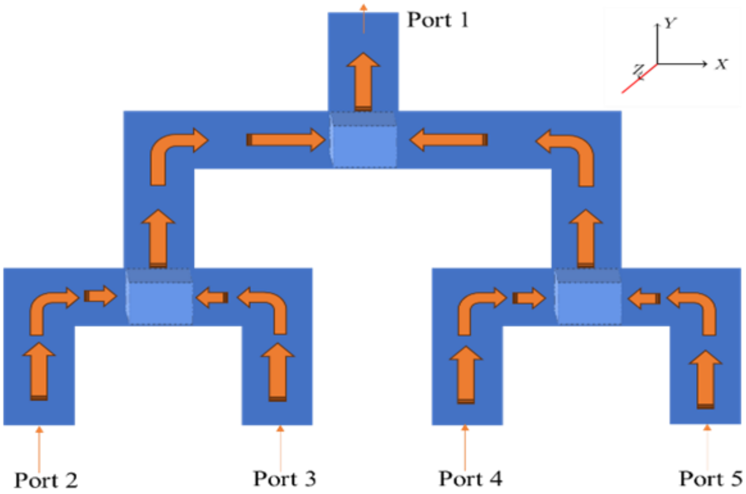

Figure 12: Schematic diagram of the signal flow in the combiner

Through thorough design, precise engineering, and adherence to fundamental principles, these combiners enable the realisation of high-performance RF systems across a wide range of applications, highlighting their critical position in modern communication, radar, and wireless technologies. The design, shown in Figure 13, was simulated using the electromagnetic simulation software CST Simulation Suite. The simulation was conducted for the frequency range of 32 GHz to 38 GHz, as it is the median sub-band within the Ka-band. When simulated for this range, the combiner has the potential to yield better results for both extremes of the band. Firstly, a magic tee was simulated with the dimensions as illustrated in Figure 14. Figure 15 shows the simulated Magic-tee. Magic-tee is composed of 4 ports, in which the input signals come from either the E-port or

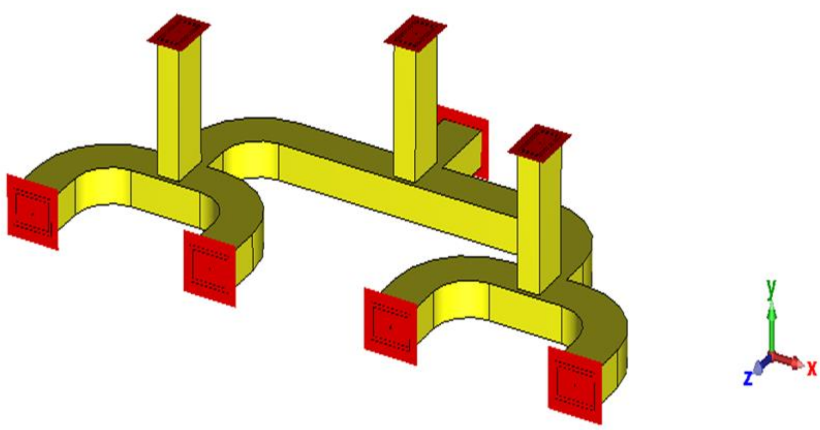

Figure 13: Simulated combiner model in the CST software

H-port and are directed towards the collinear ports through which they are divided equally. The magic tee's significance lies in its ability to divide input power into two output ports while maintaining high isolation between them. This attribute makes it ideal for applications such as radar systems, communication systems, and antenna arrays. Here, the input signal comes through the H-port and passes through the collinear ports.

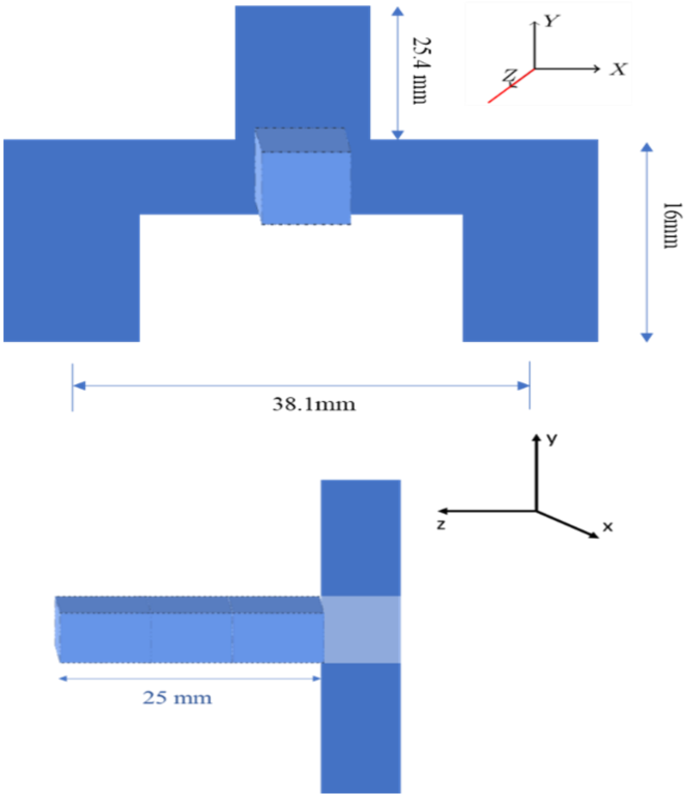

Figure 14: Illustration of the designed magic-tee's dimensions

An ideal power combiner can be used in conjunction with various impedance matching techniques to minimise signal loss through reflection.

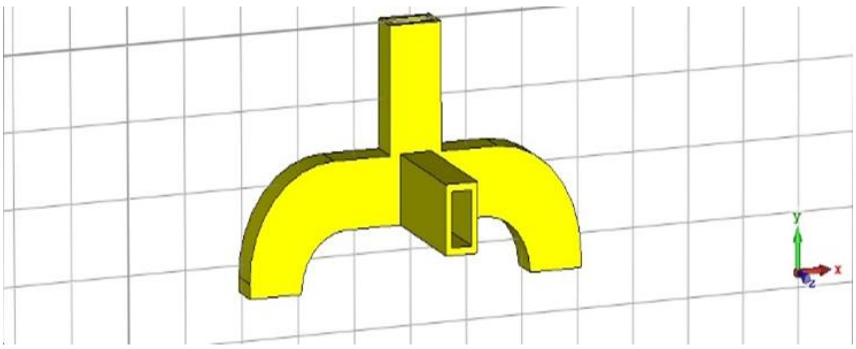

Figure 15: Simulated magic-tee in the CST software

In this paper, we employed the cylindrical posts tuning method, as illustrated in Figure 16. The precise dimensions and positioning of cylindrical posts are pivotal for realising the desired impedance transformation. By fine-tuning these parameters, the posts effectively modify the impedance observed at their inputs to align with the impedance of the connected loads or output ports. The cylindrical projection was placed inside the cavity of the magic tee, on the wall connecting the collinear arms, in a manner that minimised reflections. The parametric sweep feature of the simulation software was utilised, which varies the parameter values within a specified range for a specified number of samples and generates output for each sample. Based on the obtained outputs, the best parameters for generating the output were selected for the final design. The dimensions of the posts used are as follows:

- Radius = 1 mm

- Height = 2 mm

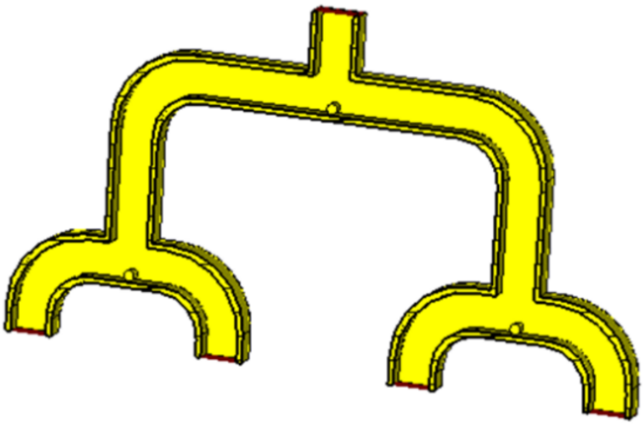

Figure 16: Position of the cylindrical posts inside the waveguide combiner

As seen in Figures 13, 15, and 16, the edges of the component are blended to reduce reflection and smooth the signal's travel. Substituting curved corners for sharp edges reduces unintentional radiation and reflection. The final optimised magic tee was then replicated to create the four input ports. The two magic-tees were connected with another WR28 waveguide with a length of 70.35 mm, as shown. Then, the output port was added to the component, finishing the construction of the combiner. Once the entire power combiner component was designed and the final simulation was completed, desirable results were obtained. Ports were assigned for each E-arm of the magic-tees and were simulated in monitor-only mode, as no signals passed through them. The four input ports were excited to observe the combined signal characteristics at the output port. Figures 17 and 18 show the final assembly of the 4-way power combiner after hardware fabrication. Coaxial adapters can be added at the input ports to normalise the impedance to 50 ohms, matching the standard impedance of the coaxial transmission line to the characteristic impedance of the waveguide.

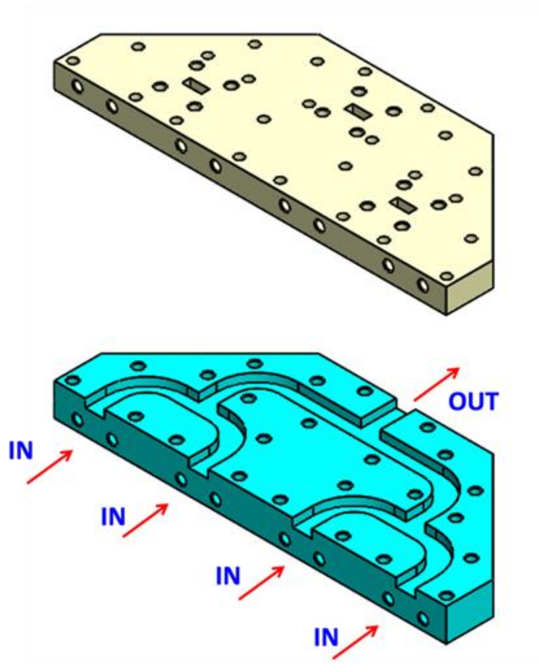

Figure 17: Exploded view of the 4-way power combiner bottom and top plate

Fringing fields are a prevalent phenomenon in transmission lines, which are conductive structures that carry electrical impulses from one location to another.

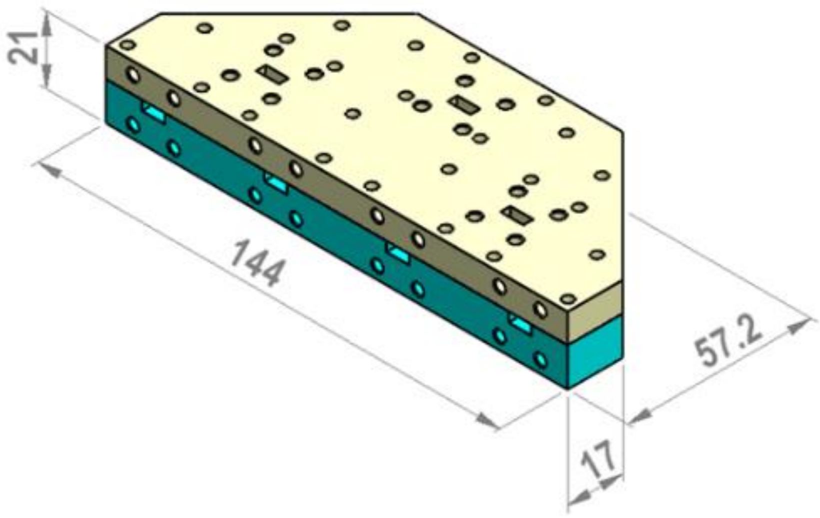

Figure 18: Assembly of the 4-way power combiner

These fields arise at the borders of the transmission line conductors and can have several consequences on the transmission properties of the line:

- **Capacitive Effects:** Fringing fields generate capacitance between transmission line conductors and the surrounding environment. This capacitance affects the transmission line's impedance, which can lead to impedance mismatches, signal reflections, and signal integrity loss. At high frequencies or in high-speed digital systems, the capacitance generated by fringing fields becomes increasingly important, which can compromise the performance of the transmission line.
- **Propagation Delay:** Fringing fields affect the effective propagation velocity of signals along the transmission line. The electric field associated with fringing can cause delays in signal propagation, resulting in distortion and skew in transmitted signals. This impact is most pronounced in transmission lines with high dielectric constants or in systems that operate at high frequencies, requiring precise signal timing.
- **Cross Talk:** Fringing fields can cause crosstalk between adjacent transmission lines or conductive structures. When numerous transmission lines are routed near each other, the fringing fields from one line can couple onto neighbouring lines, resulting in interference and distortion. This crosstalk can result in signal deterioration and lower system performance, particularly in densely packed electronic systems or in high-speed data communication applications.
- **Losses:** Fringing fields cause dielectric losses in the surrounding medium, notably in insulating materials or dielectrics near the transmission line conductors. These losses can weaken sent signals and lower the overall efficiency of the transmission line. Minimising fringing fields and optimising transmission line structural design can help to reduce losses and increase signal transmission performance.

In summary, fringing fields in transmission lines have significant effects on signal propagation, impedance characteristics, crosstalk, and signal integrity. Understanding and properly managing these effects are essential for designing high-performance transmission line systems in various applications, including telecommunications, high-speed data transmission, and RF (Radio Frequency) engineering. By carefully considering the impact of fringing fields in transmission line design, engineers can optimise signal transmission performance and ensure the reliable operation of electronic systems.

3.1. Design Characteristics

3.1.1. S-Parameters

Figure 19 below provides insight into the three important S-parameters. Assuming the input is port one and the output is port 2 in this 2-port illustration of a rectangular waveguide. A represents the power the waveguide is supplied with, and b represents the power reflected. Here, we have four different terms, namely S11, S12, S22, and S21, as shown in Figure 19. These are the key parameters to consider, not only when working on power combining but also in the broader field of RF and microwave engineering.

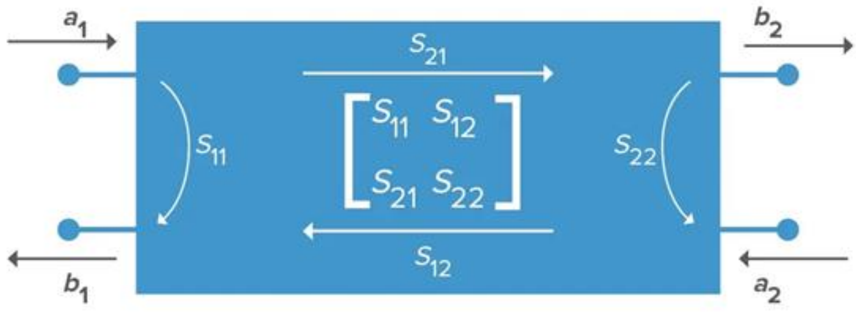

Figure 19: S-parameters

3.1.2. Return Loss

First, let's examine S11, which represents the return loss at port 1. The mathematical equivalent of this is the ratio between the reflected output power and the total input power at port one, which is given by equations (5) and (6).

$$S_{11} = \frac{V_{reflected}}{V_{incident}}, \text{ at port 1} \tag{5}$$

$$\text{Return loss at port 1} = [-20 \log_{10} |S_{11}|] \tag{6}$$

Similarly, S22 is the return loss at port 2. The mathematical equivalent of this is the ratio between the reflected output power and the total input power at port 2, as given by Equations (7) and (8).

$$S_{22} = \frac{b2}{a2} \tag{7}$$

$$\text{Return loss at port 2} = [-20 \log_{10} |S_{22}|] \tag{8}$$

A good waveguide must have both S11 and S22 as low as possible. They are measured in dB. Ideally, it should be 0, but this is impossible to achieve in a real-world scenario.

3.1.3. Insertion Loss

Next, we shall move on to the insertion loss, which occurs during the transmission or power through the waveguide. Insertion loss represents the difference in signal power or amplitude before and after the insertion of the component. It refers to the reduction in signal power or amplitude that occurs when a component, device, or system is inserted into a transmission line or circuit. This is the loss due to the loss during the transmission, from the input (port 1) to the output (port 2). The mathematical representation of insertion loss is given by equations (9) and (10). And, vice versa, as shown by equations (11) and (12) for S12.

$$S_{21} = \frac{b2}{a1} \tag{9}$$

$$\text{Insertion loss at port 1} = [10 \log_{10} |S_{21}|] \tag{10}$$

$$S_{12} = \frac{b1}{a2} \tag{11}$$

$$\text{Insertion loss at port 2} = [10 \log_{10} |S_{12}|] \tag{12}$$

Reasons for insertion loss in our devices can range from impedance mismatches, attenuation, scattering, absorption, to other losses within the component or transmission line. These factors may also occur due to inherent properties of the materials used, design considerations, manufacturing tolerances, and environmental conditions. At a certain point, it becomes impossible to remove, and hence, we must try to minimise the losses due to the problems mentioned above.

3.1.4. Isolation Loss

Finally, we have the isolation loss. This refers to the loss resulting from the coupling that occurs between the ports. This must be reduced by limiting the chance of the two ports communicating with one another to zero. Isolation loss is a concept integral to the understanding of electronic systems, particularly in the domains of RF, microwave engineering, and telecommunications. It describes the attenuation or reduction in signal strength between two ports of a device or network when the signal is intended to flow only in one direction. Isolation loss is typically expressed in dB and represents the difference in signal power or amplitude between the output port and the isolated port of a device.

3.1.5. VSWR

Voltage Standing Wave Ratio VSWR is a fundamental parameter used to characterise the performance of RF systems, particularly in the context of antennas and transmission lines. VSWR is also used to indicate the loss of signal due to impedance mismatch, among other factors. It is a measure of the ratio of the maximum voltage to the minimum voltage at the input/output terminals of an antenna, as shown by equation (13). The standing wave is shown in Figure 20.

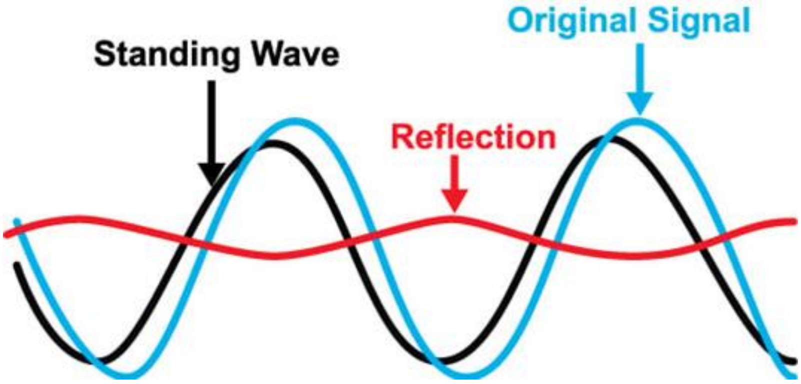

Figure 20: Standing wave

It is a measure of how efficiently radio-frequency power is transmitted from a power source, through a transmission line, and into a load. In an ideal system, 100% of the energy is transmitted, having $\Gamma = 0$ and VSWR = 1. However, this is not entirely realistic, so a VSWR of 1.1 or 1.2 is considered reasonably good. The VSWR of a good combiner must also not exceed 2.

$$\text{VSWR} = \frac{V_{max}}{V_{min}} \quad (13)$$

VSWR is based on a parameter called the reflection coefficient (Γ), which is represented by equation (14).

$$\Gamma = \frac{Z_L - Z_O}{Z_L + Z_O} \quad (14)$$

where, ZL= load impedance and Z_O= characteristic impedance. From equation (14), the VSWR can be derived as shown by equation (15).

$$\text{VSWR} = \frac{1+|\Gamma|}{1-|\Gamma|} \quad (15)$$

4. Results and Discussion

4.1. Insertion Loss

Insertion loss in a 4:1 waveguide power combiner refers to the amount of signal power lost when multiple input signals are combined into a single output. It measures the difference in power between the input signals and the combined output signal. In this context, the insertion loss specifically indicates how efficiently the combiner merges the input signals without significant power loss. Ports 2, 3, 4, and 5 are excited simultaneously with the same input power and phase, and the combined output power at port one is plotted in Figure 21. Ideally, combining power requires a gain of 6dB to be achieved, but this is slightly less due to power loss during the combining process. The insertion loss obtained is 0.5 dB.

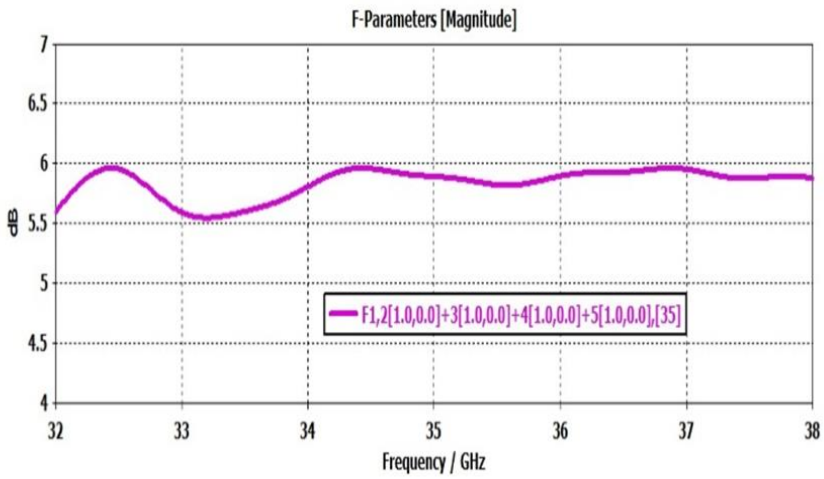

Figure 21: Simulated combiner output in the CST software

4.2. Return Loss

Return loss in a 4:1 waveguide power combiner refers to the amount of power reflected towards the input port due to impedance mismatches. It measures the proportion of signal power that is not transmitted through the combiner and instead is reflected. A lower return loss indicates better impedance matching and less power being reflected towards the input, which is desirable for efficient signal transmission. Figure 22 shows a plot of the return loss at port 1 (S11) when all the ports were excited. It achieves the desired value of less than -10 dB.

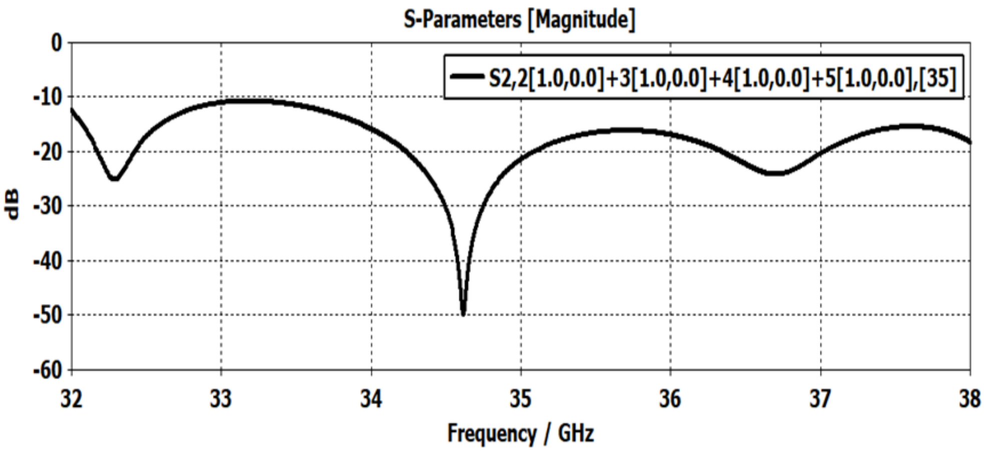

Figure 22: Simulated S11 at one of the input ports

The significance of return loss in RF combiners is multifaceted. For starters, it serves as a statistic for evaluating the quality of impedance matching at the input port. A higher return loss indicates better impedance matching, meaning that less power is reflected to the source. This effective power transfer guarantees that the available signal is optimally utilised while also minimising signal degradation or interference inside the system.

4.3. Isolation Loss

Isolation loss in a 4:1 waveguide power combiner refers to the amount of attenuation or reduction in signal strength between different output ports. It measures the combiner's ability to isolate or separate the input signals from each other at the output ports. Higher isolation loss values indicate poorer isolation between the output ports, meaning that the signals intended for one port may leak into other ports. Lower isolation loss values imply better separation between the output ports, minimising interference and ensuring that each port receives its intended signal with minimal contamination from other ports. Figure 23 shows the plot of the isolation loss between 2 input ports. From the plot, it can be inferred that maximum isolation is achieved, resulting in no coupling between the ports.

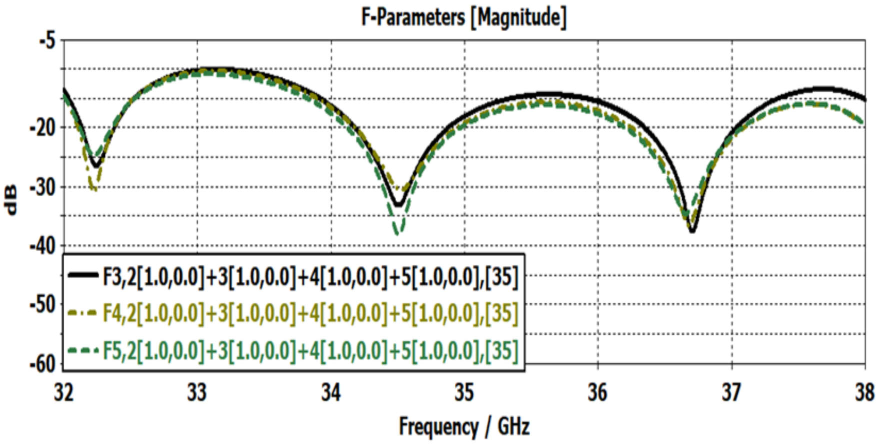

Figure 23: Simulated isolation loss between input ports

High isolation loss indicates poor isolation between the ports, meaning that there is significant signal leakage or coupling between them. Conversely, low isolation loss suggests that the device effectively isolates the signals at different ports, minimising interference and ensuring that each port operates independently. In applications where multiple signals need to be combined or split without interference, such as in RF and microwave systems, achieving high isolation between ports is crucial. This helps to maintain signal integrity, prevent crosstalk, and ensure the proper functioning of the system.

4.4. VSWR

VSWR, or Voltage Standing Wave Ratio, in a 4:1 waveguide power combiner, reflects the ratio of the maximum voltage to the minimum voltage along a transmission line. It measures how well the load impedance matches the transmission line impedance. VSWR values are typically between 1 and infinity, where 1 indicates perfect impedance matching (no reflections) and higher values indicate poorer matching.

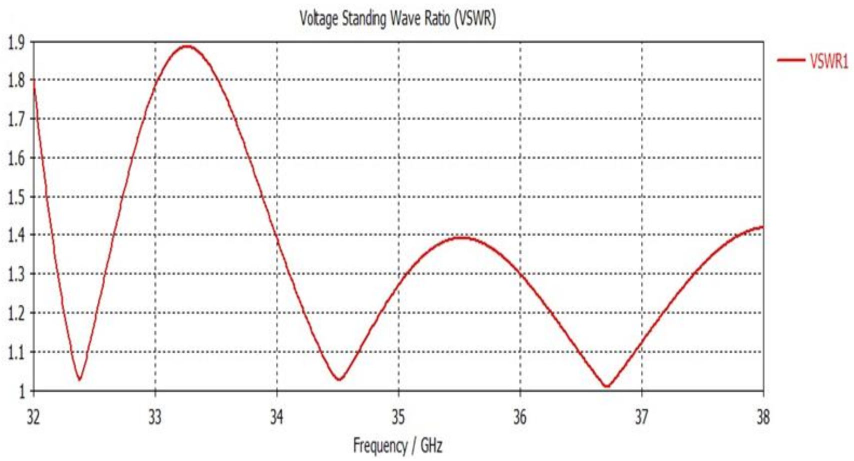

Figure 24: VSWR at port 1

In this context, a VSWR between 1 and 2 indicates good impedance matching, meaning minimal signal reflections and efficient power transfer. Figure 24 shows the plot of VSWR at port 1, obtained between ranges 1 and 2. Well-established principles and methodologies guide the measurement and interpretation of VSWR. VSWR can be calculated using various techniques, including direct measurements using specialised instruments such as vector network analysers or through indirect methods based on reflection coefficients. Regardless of the method employed, VSWR serves as a critical diagnostic tool for RF engineers, offering insights into the quality of impedance matching and the overall health of RF systems.

The practical significance of VSWR spans across a wide range of RF applications, from wireless communication systems to radar and satellite technologies. In antenna systems, for instance, VSWR directly impacts transmission efficiency, signal quality, and coverage range. A high VSWR in an antenna system can lead to increased signal loss, distorted waveforms, and reduced transmission range, compromising the performance and reliability of the entire RF system. Moreover, VSWR plays a pivotal role in the design, optimisation, and troubleshooting of RF systems. By accurately measuring and analysing VSWR, engineers can identify and mitigate impedance mismatches, optimise antenna designs, and ensure the proper functioning of transmission lines and RF components. Furthermore, VSWR serves as a key parameter in quality assurance and acceptance testing of RF systems, enabling engineers to validate system performance and compliance with specifications.

4.5. Simulation Waveform

Figure 25 shows the colour-coded simulation waveform as it proceeds further into the combiner and towards the output port; the colour of the wave changes. This is indicated by the scale provided on the left-hand side of the picture. As the strength of the electric field increases, the colour of the light changes. First, we can see the wave in dark blue, indicating there is a lesser electric field strength.

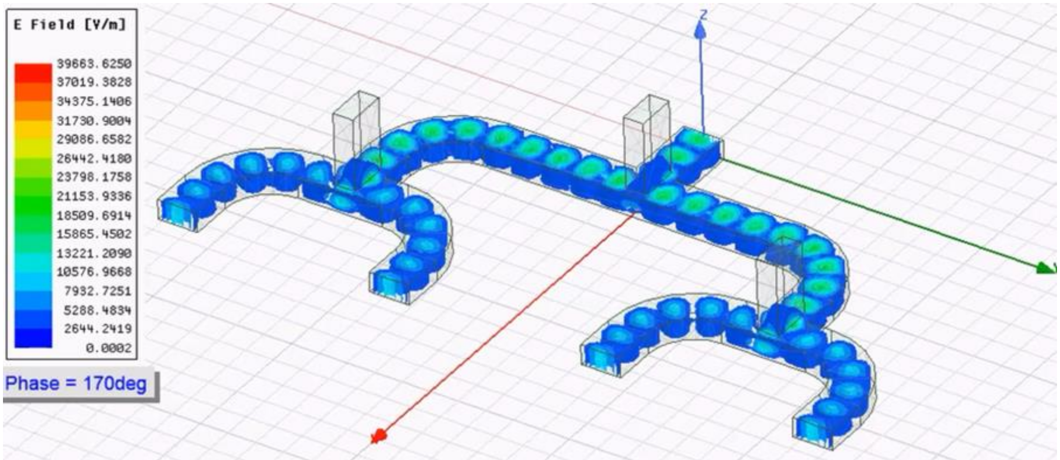

Figure 25: Colour-coded simulation waveform

But as we proceed further into the combiner, we notice the core of each wave is reaching a stronger electric field strength. This can be inferred from its transition from dark blue to light green. The comparison of the results of the existing and proposed models is shown in Table 1.

Table 1: Comparison of results between existing and proposed models

Parameters	Existing Model Results	Proposed Model
Frequency Range	27GHz-32 GHz	32GHz-38GHz
Return Loss	20dB	13dB to 50dB
Isolation Loss	8dB to 14dB	15dB to 35dB
Insertion Loss	0.54 dB	0.5 dB

5. Conclusion

In conclusion, this research paper presents the design and analysis of a 4-way Ka-band power combiner utilising a rectangular waveguide, achieving high isolation and gain. The existing model, consisting of an embedded microstrip-to-waveguide transition, is completely substituted by rectangular waveguides, which is a better solution for getting low-loss output over the entire bandwidth. The existing model achieves the desired output specifically at 32 GHz, and it also extends to higher frequencies, up to 38 GHz, providing the desired insertion loss, return loss, and isolation loss. The proposed model can be used in high-frequency RF applications with minimal loss. Through detailed theoretical analysis and simulated performance, the proposed power combiner has been evaluated, demonstrating its effectiveness in combining multiple input signals into a single output with minimal loss and high efficiency within the Ka-band frequency range.

This approach to power combining holds significant promise for a wide range of applications in radar systems, communication networks, and other RF and microwave systems operating in the Ka-band. The simulated model will be fabricated using aluminium as the base material and plated with silver due to its high conductivity and low-loss properties. Future research directions may focus on further optimising the design parameters of the power combiner, exploring alternative waveguide transition techniques, and investigating potential applications in emerging Ka-band technologies. Overall, the development of the 4-way Ka-band power combiner represents an efficient waveguide-based signal combining technology, with potential implications for the development of high-frequency microwave systems.

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Data Availability Statement: The study utilises a dataset that contains information on a 4-to-1 microwave power combiner/amplifier for Ka-band frequencies, employing a rectangular waveguide with a cylindrical post tuning technique for impedance matching. The dataset can be made available upon reasonable request to the corresponding authors.

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Ethics and Consent Statement: The authors confirm that consent was obtained from the organization and all participants during data collection, and that ethical approval and participant consent were duly received.

References

1. A. Patel, “Design and Fabrication of Microwave Waveguide Resonator: With improved Characteristic response,” *European Journal of Scientific Research,* vol. 102, no. 2, pp. 163-174, 2013.
2. A. Rajesh, R. Vani, and B. Rama Rao, “Performance Analysis of Rectangular Microstrip Wearable Textile Antenna with Series of Slots,” *Journal of Communications.* vol. 17, no. 5, pp. 365-372, 2022.
3. B. Ozturk and O. Coskun, “Design of wideband microstrip power divider/combiner with input and output impedance matching for RF energy harvesting applications,” *Int. J. RF Microw. Comput-Aid. Eng.,* vol. 29, no. 1, pp. 1–7, 2019.
4. F. A. Shaikh, S. Khan, A. Z. Alam, M. H. Habaebi, O. O. Khalifa, and T. A. Khan, “Design and analysis of 1-to-4 wilkinson power divider for antenna array feeding network,” *in 2018 IEEE International Conference on Innovative Research and Development (ICIRD),* Bangkok, Thailand, 2018.
5. F. Miligy, “Design and Analysis of X-Band Waveguide Feeder Structure with Dominant Mode Transmission Enhancement Using Tuning Stubs,” *in 2021 International Telecommunications Conference (ITC-Egypt),* Alexandria, Egypt, 2021.
6. J. Ye, H. Zhang, and R. Chu, “Analysis of a new method to design a coaxial-to-rectangular waveguide transition,” *in 2019 International Applied Computational Electromagnetics Society Symposium - China (ACES),* Nanjing, China, 2019.
7. M. Hoari, H. Bousbia, H. Boutayeb, A. Martin, and P. Blondy, “A novel compact Four-Way power combiner with an embedded microstrip-to-waveguide transition for Ka-band power amplifiers,” *in 2021 51st European Microwave Conference (EuMC),* London, United Kingdom, 2022.
8. M. Mansouree and A. Yahaghi, “Planar magic-tee using substrate integrated waveguide based on mode-conversion technique,” *IEEE Microw. Wirel. Compon. Lett.,* vol. 26, no. 5, pp. 307–309, 2016.
9. M. Moallem, J. East, and K. Sarabandi, “A broadband, micromachined rectangular waveguide to cavity-backed coplanar waveguide transition using impedance-taper technique,” *IEEE Trans. Terahertz Sci. Technol.,* vol. 4, no. 1, pp. 49–55, 2014.
10. P. Neininger, M. Zink, L. John, C. Friesicke, A. Tessmann, R. Quay, and T. Zwick, “16-way Ka-band power combiner using novel waveguide transitions,” *IEEE Transactions on Microwave Theory and Techniques,* vol. 70, no. 6, pp. 3074–3086, 2022.
11. S. Abbas, M. Maqsood, N. Shoaib, M. Q. Mehmood, M. Zubair, and Y. Massoud, “A wideband RF power divider with ultra-wide harmonics suppression,” *IEEE J. Microw.,* vol. 3, no. 4, pp. 1248–1257, 2023.
12. Y. Kang, X. Jin Pin, and C. Zheng Hua, “A full Ka-band waveguide-based spatial power-combining amplifier using e-plane anti-phase probes,” *in 2014 IEEE International Wireless Symposium (IWS 2014),* X'ian, China, 2014.
13. Y. L. Luo, Q. Li, and J. H. Zha, “A new high isolation 3dB divider/combiner for Ka band power-combining amplifier,” *in 2011 International Conference on Computational Problem-Solving (ICCP),* Chengdu, China, 2011.