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Designing and Analysis of Folded H- Plane Waveguide Power Combiner For K-Band

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Abstract:
This research work presents the design and numerical analysis of a folded K-band electromagnetic structure i. e. power divider/combiner for operating frequency range from 18 GHz to 26 GHz. A three-dimensional multilayer geometry was modelled and optimized using CST Microwave Studio. The proposed structure shows selective transmission behaviour, supporting two distinct propagation paths characterized by S_{21} and S_{31}. The simulated results depict deep resonances between 22–23.6 GHz, moderate passband behaviour in the 24–26 GHz range, equal power division between 18-21 GHz. The compact structure of the design—using dielectric sections in cascaded form and metallic boundaries—makes it suitable for integrated microwave systems, filtering networks, and compact front-end modules.

Keywords: K-Band, S-parameter, CST, 3 dB, PEC.

Introduction

The K-band (18-26 GHz) continues to play a critical role in satellite communications, radar imaging, high-resolution sensors, and point-to-point wireless links [1, 2]. Structures that demonstrate selective transmission properties while taking up the least amount of physical space are becoming more and more necessary as system topologies move towards more compact and multipurpose RF modules. In-depth investigation of unusual geometries that can accomplish high-performance filtering, coupling, or power division functions without undue complexity is made possible by numerical electromagnetic solvers like CST Microwave Studio [3-6].

When we look at high-frequency systems we can see that they need based power combiners to get higher output power levels. High-frequency systems need to keep the insertion loss low. The phase characteristics of high-frequency systems stable, at the same time.

When we use systems with K-band we have to think about the losses that happen in the conductors and the tolerances that come with making things. These things are more of a problem in K-band systems. In these situations rectangular waveguides are a choice than transmission lines for K-band systems [6]. We find that rectangular waveguides work better for K-band, than transmission lines do.

We have kinds of waveguide configurations that we can use. One type is the H-plane combiner. The H-plane combiner is used a lot. This is because it has a field distribution that's symmetric.

This means the H-plane combiner is not as sensitive to mistakes that happen when it is being made. We like the H-plane combiner for these reasons.

H-plane combiners and other types of power combiners are important for things, like high-frequency systems and K-band applications [12]. The thing is, traditional H-plane power combiners have a problem. H-plane power combiners are long and they do not bend easily when you try to put H-plane power combiners into small systems. This is a problem with H-plane power combiners because H-plane power combiners need to be compact.

H-plane power combiners are just not good, at being small and H-plane power combiners are not flexible either. People are looking at folded geometries as a way to make things smaller.

Folded geometries are a solution to these problems. When we bend and fold the waveguide we can keep the path of the waveguide the same length but the whole thing becomes a lot smaller.

The waveguide can be made smaller by folding it.

This means we can pack the other things in tightly and the waveguide also works better with other parts, like the filters the transitions and the amplifiers that are nearby the waveguide. When you put bends and junctions in the waveguide it messes with the fields around it. Resonances and impedance mismatches problems may occur due to these structural modifications. We also have to take frequency- coupling effects into considerations with the folded waveguide geometries. The folded waveguide geometries are still something we can use. We have to be precautionly because of these problems.

The electromagnetic fields and how they work with the waveguide must be observed to make sure the power is stable and works like in expected way. We have to do this so that the waveguide works well and the power's stable. The waveguide and the electromagnetic fields are important to consider when we are trying to make sure everything works correctly. This is really important. We need to make sure the power combining is balanced. It has to work across all the frequencies that the power combining system is supposed to work on. We are looking at the power combining system to see how it works. The analysis of the power combining system is what we are talking about. We want the power combining system to do its job right.

The wave simulation is really important for understanding the things that happen inside the folded waveguide structures.

The wave simulation helps us to see what is going on. Time domain solvers are very good for looking at a range of frequencies. This is because they can give us information about how signals scatter over many different frequencies all, from one wave simulation of the waveguide structures. We can get a lot of information from one wave simulation.

We can learn a lot from things like transmission coefficients S_{21} and S_{31}. These things tell us about how power's divided when the phases are consistent and how efficient the combining of power is. Simulations in time-domain solvers is best way to understand how folded waveguide structures work and to analyze what is going on with the fields and modes inside the parts rather than to analyze with mathematical techniques.

This study is about a kind of power combiner for K-band. We are looking at power combiners, for K-band. How they work. This thing is a folded H-plane power combiner [12]. We used CST Microwave Studio to figure out how it works. The power combiner is supposed to combine power from the power sources. It is also supposed to be small so it does not take up a lot of space and have impedance matching so the power combiner works properly with the power sources. The power combiner is made to combine power. It has to be small.

We took a look at how it works with different frequencies. We were trying to figure out which frequencies are good for power combining. At the time we wanted to see which frequencies do not work very well with the folded shape of the power combiner. The folded shape really affects some frequencies so we wanted to know which ones are not good, for it. We focused on the frequencies that work well with power combining and the ones that do not work well because of the folded shape.

The results we got are really good. This power combiner works well and it gives us the results we want. It works well across the K-band range. We were actually targeting the K-band range with the power combiner. The power combiner and the K-band range are what we were focusing on.

The folded H-plane waveguide power combiner is really good. It is small. It works with electricity and high frequencies. This is what makes the folded H-plane waveguide power combiner a great choice for things like satellite systems, radar systems and wireless communication systems.

The work that is done here is very helpful because it makes waveguide components smaller. It shows that using folded shapes along, with computer simulations is a good way to design microwave subsystems for the future. The folded H-plane waveguide power combiner is an it’s example.

The use of systems having operating frequency range from 12-26 GHz is becoming crucial in satellite communication, radar sensing and frequency wireless links. This has led to a lot of research on structures that can handle microwave frequencies in a stable and selective way[8]. K- and Ku-band frequency [5] range systems are really useful in these areas.

Makimoto and Yamashita sprcifird some work on microwave resonators and filters. They observed K- and Ku-band systems to analyze how to control resonance, shape bandwidth and deal with loss mechanisms. Their work was important. It helped us understand how these systems work. K- and Ku-band systems are still an area of research today. Their work on this topic was really important because it helped create an idea that we still need today to understand how some parts work. These parts are called waveguides and resonators. They work with special kinds of waves at very high frequencies, like microwaves and millimeter waves. The thing they figured out is still essential, for understanding how these parts behave when they pick and choose which frequencies to work with. This is what we call frequency- behavior in waveguides and resonators that operate at microwave and millimeter-wave frequencies.

So we have an idea of how things work. Now people are really looking into electromagnetic coupling mechanisms to control how signals are sent. Hong and Lancaster did some work, on this with microstrip open-loop resonators. They showed that by making the resonators interact with each other in a controlled way we can create transmission zeros and make the signal more selective. They were working with structures but the ideas they talked about also apply to three-dimensional waveguide junctions. In these junctions how the fields interact between parts is what determines how power is transferred and how the frequency responds. Electromagnetic coupling mechanisms are important here because they help us understand how the fields interact.

System architectures have changed over time to make things smaller and more compact. This led to a lot of research on ways to make things smaller without losing performance. Wu came up with something called substrate circuits. These circuits combine the things about waveguides, which have low loss with the advantages of planar fabrication. This work showed that we need to make electromagnetic structures smaller, for millimeter-wave applications. It also showed that we need to think of creative ways to arrange things to make them smaller without making them work worse. Millimeter-wave applications need electromagnetic structures to work well.

Researchers were also trting to make compact power divider/combiner designs that have the ability to perform well with broadband operation and keep transmission stable.

Abbosh and Bialkowski showed that miniaturized directional couplers can be used for wideband microwave applications. They found out that if you optimize the parts carefully you can make compact sizes and good coupling efficiency work together. This is really important for folded structures, where you have to use the available electromagnetic path length in a very efficient way because space is limited. The compact coupler designs (as per specifications) are useful, for these folded structures.

The role of sections is really important for getting good performance across a wide range of frequencies. Gómez-García and Alonso looked into this. They came up with a idea for hybrid couplers that use many resonant sections to get wideband performance. What they found out is that the resonances that happen over the place can be used to make the bandwidth better and get a more balanced signal. This idea is similar to what happens in folded power combiners, where the bends and junctions in the waveguide cause resonant effects that affect how the signal passes through and how much it gets weakened. Resonant sections play a part, in this.

Compact resonators work well at frequency bands for high-stability operation. Sharma and his team found a way to make a Ku-band dielectric resonator that is good for satellite systems because it is compact and has a stable frequency. This shows that compact resonators can be used for high-frequency operation. The design ideas they came up with can also be used for K-band folded components. Compact resonators are useful, for these kinds of systems.

Recent studies have shown that folded shapes are really good at controlling how electromagnetic waves behave and they can do this while being smaller. Maxworth looked at folded monopole antennas. Found out that when you fold them it changes how the current moves and how they resonate but it does not hurt how well they send out radiation. Even though this work was about antennas it helps us understand how folding affects how the fields are contained which is also very important, for folded power combiners. Folded power combiners can benefit from this knowledge about folding and how it modifies field confinement just like folded monopole antennas do.

Guo and other people showed that a special kind of antenna called a folded transmitarray antenna can work well. This antenna can control how it sends out and scatters radiation. This is an example of how folded designs are being used more and more in advanced microwave systems. The results of Guo and other people prove that folded designs can make things smaller without losing control of how they work with electricity and magnetism. This is a reason to use folded designs, in other parts of microwave systems like waveguide combiners, where we do not want radiation to be sent out.

The literature I looked at shows that resonant behavior and electromagnetic coupling're really important for modern microwave components. They also need to be designed in a way. There are a lot of studies on resonators and hybrid couplers and folded antennas.. Not many people have looked at folded H-plane waveguide power combiners that work in the K-band. Microwave components, like these folded H-plane power combiners are interesting because they can operate in the K-band. This observation directly supports the motivation of the present work, which focuses on analyzing a compact folded H-plane waveguide power combiner using full-wave electromagnetic simulation to achieve controlled transmission characteristics within the K-band.

I. STRUCTURE DESIGN

Figure 1 illustrates the full CST model used in simulation. The geometry is composed of several dielectric blocks, metallic inserts, and air gaps arranged asymmetrically along orthogonal axes. Key features include:

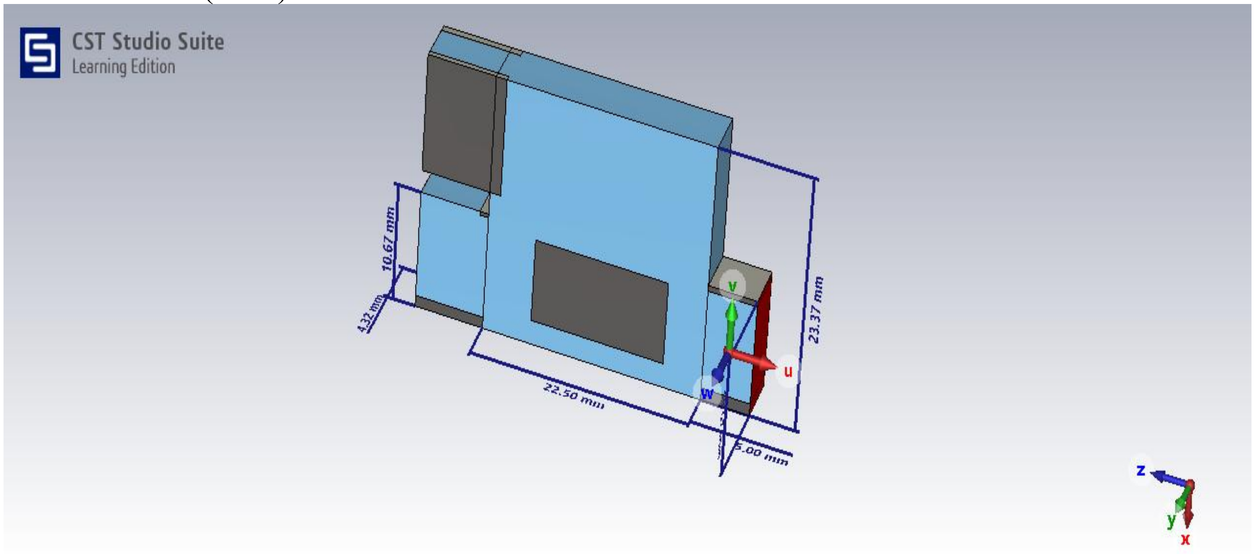


Figure 1: Dimensional view of H-plane power divider/combiner

- **Stacked dielectric segments** of varying width and height that tune the local phase velocity and impedance.
- **A metallic side section** (shown in red) acting as a resonant boundary that shapes the high-frequency rejection behaviour.
- **Precision-controlled dimensions**, such as 4.32 mm, 5.00 mm, 10.67 mm, and 23.37 mm segments, which create coupled resonant cavities.
- **Coordinate system vectors (u, v, w)** marking the primary directions of propagation and adjustment during optimization.

The entire arrangement looks like a compact, unusual filter topology [5, 7]. The combination of dielectric loading and geometric discontinuities creates many resonant modes over the K-band.

II. SIMULATION METHODOLOGY

The structure was looked at using the time-domain mode solver in CST Microwave Studio. This was done to see how the structure behaves in space. The analysis was set up with boundaries to make it seem like the structure is, in open space [7, 8]. The ports were put in place to test and measure the ways that signals travel through the structure. There are two paths that the signals take: the Main transmission path and the Coupled or secondary transmission route, which are also known as S_{21} and S_{31} respectively.

We performed a simulation for a range of frequencies that went from 18 GHz to 26 GHz. The simulation was done with a lot of steps so we could see the sharp resonances really clearly. We kept adjusting the material characteristics and mesh settings until the simulation gave us results. This was done times to make sure the simulation was working properly for the frequency range of the simulation, which was 18 GHz, to 26 GHz.

The proposed folded K-band power divider/combiner structure was analysed [12] using the time-domain solver in CST Microwave Studio, chosen for its suitability in characterizing resonant and dispersive components [9- 11]. The simulation procedure was designed very carefully to give the surity that the numbers were correct and that the fine electromagnetic details brought out by the geometry in Figure 1 were captured.

3.1 Model Preparation and Material Assignment

All dielectric blocks and metallic regions were modelled as statiscally separate three-dimensional units. The dielectric sections were assigned their respective permits based on design requirements, as perfect electric conductors (PEC) in the form of metallic boundaries were treated to minimise computational load. For exploratory iterations, dispersive models were temporarily removed; however, final simulations included frequency-dependent permittivity for improved realism.

The internal resonance behaviour is very much influenced by air gaps, were explicitly included as separate domains to preserve correct field continuity at material interfaces.

3.2 Port Configuration and Excitation Strategy

Two waveguide ports were positioned to excite the structure along orthogonal directions.

i). Port 1 required to excite the main propagation path, yielding the S_{21} response.

ii).Port 3 (secondary port) was used to observe the cross-coupling and alternative propagation modes, producing the S_{31} response.

Each port supported the fundamental TE/TM propagation mode. The solver automatically computed the modal field distribution to ensure consistent excitation across the entire k-band frequency range [11, 12]. The port's size was choosen in such a way that the boundaries were sufficiently away (isolated) from the physical structure to avoid unwanted reflections.

3.3 Boundary Conditions and Computational Domain

All of the simulation regions' outside sides had open (radiation) boundary conditions. This method stops fake field confinement and comes very near to how things behave in free space. The computational domain was expanded beyond the physical geometry by incorporating an additional buffer region to ensure that evanescent fields dissipated prior to reaching the boundaries, hence minimising numerical reflections.

At the outermost boundary of the simulation, a perfectly matched layer (PML) termination was added [11]. This method makes things more accurate at higher frequencies, where field leakage is more of a problem.

3.4 Meshing Strategy

A hybrid tetrahedral–hexahedral mesh was used to provide high resolution in regions with strong field gradients, such as:

- dielectric–air interfaces
- metallic edges
- narrow coupling sections
- steep dimensional transitions

The mesh was locally refined around the resonant cavities to accurately resolve the standing-wave patterns that generate the sharp notches as shown in Figure 2. The adaptive mesh refinement (AMR) method was executed numerous times until the S-parameters came together with only a 0.02 dB difference across the band.

3.5 Frequency Sweep and Solver Configuration

The simulation frequency was swept from 18 to 26 GHz [12] using fine-resolution sampling, especially in regions where steep gradients in S-parameters were expected. The solver's convergence criteria included:

- stable energy balance
- field solution error < 0.5%
- consistent port impedance calculation across iterations

The time-domain approach was chosen instead of a broadband frequency-domain solver because the structure reflects narrow resonances requiring higher spectral resolution.

3.6 Post-Processing and Data Extraction

After solver convergence, S-parameters were extracted and smoothed using CST’s built-in post-processing tools. Resonant frequencies, −10 dB bandwidths, and notch depths for both S_{21} and S_{31} were recorded. Field plots were also observed to visually confirm the presence of standing waves in the mid band and cavity confinement near 23 GHz.

III. RESULTS AND DISCUSSION

4.1 S-Parameter Performance

Figure 2 shows ‘the simulated S_{21} (green) and S_{31} (blue) magnitudes across the entire K-band’:

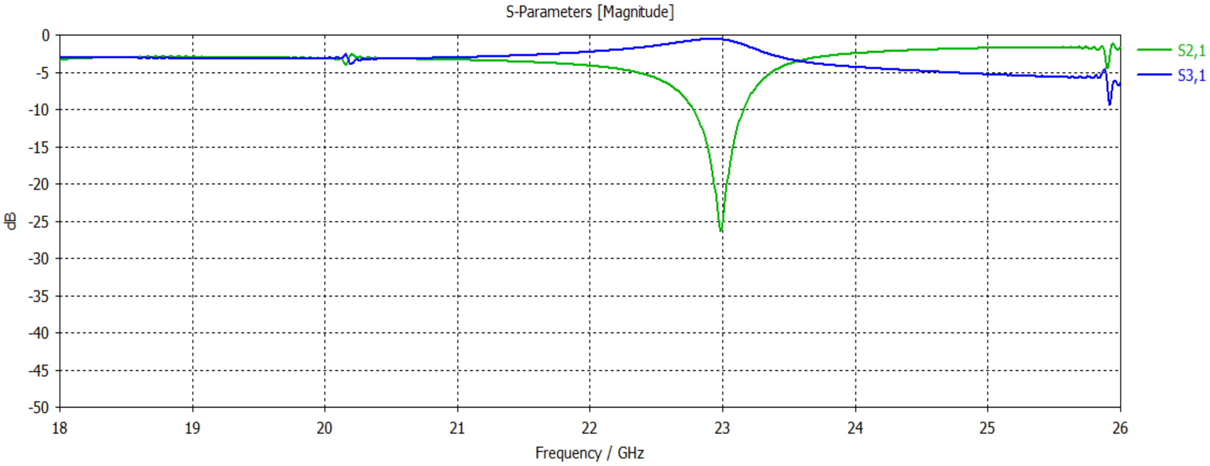


Figure 2 : Simulated S_{21} (green) and S_{31} (blue) magnitudes' plots across the entire K-band

Low-frequency behaviour (18–21 GHz)

The signal transmission is really steady in the 18–21 GHz range for both S_{21} and S_{31}. They do not change much & are very close to each other. This means that the signals are going through both paths in an uniform way. You do not see any spikes or dips, in this area. This tells us that the system is not having any resonance problems and the coupling is consistent. The system works well at frequencies. It has an insertion loss and the performance is balanced for S21 and S31.

Mid-band behaviour (21–24 GHz)

In the range of frequencies from 21 to 24 GHz the response changes a lot. 23 GHz the S_{21} response has a very deep drop it goes down very quickly to a very small magnitude, which means the frequency is blocked or attenuated a lot at this point. This is what happens when you have a resonance or a band stop effect in the frequency range. At the time the S_{21} and S31 frequency responses are doing different things the S_{31} response is going up it reaches its highest point, near 23 GHz, which means that more power is being transferred along this path at this frequency the S_{31} frequency response is showing this. This behavior is really different. It shows that the system works with specific frequencies. This means that energy is being sent in a direction instead of being spread out everywhere. The system is operating in a way that selects frequencies and redirects the energy rather than transmitting it uniformly. This frequency-selective operation is a thing to note about the system.

High-frequency region (24–26 GHz)

The responses started to settle down between 24 and 26 GHz. S21 was really low. Then it started to go up and became more steady. On the hand S_{31} went down slowly with some small changes here and there.The power division is still not equal so it does not really matter in a sense. What is good is that there are no resonances in this region, which means the frequency is not as sensitive as it is in the mid-band. This is a deal because it means the frequency is more stable in this range.

The responses of S_{21} and S_{31} are important to consider when looking at the power division and in this case the power division of the responses is not equal which is the problem we have, with the original responses of S_{21} and S_{31}. However, small ripples near the upper end may be caused by parasitic effects, impedance mismatches, or higher-order modes becoming more influential at these frequencies.

Equal-Power Division Region (18–21 GHz)

Following figure 3 shows equal power division:

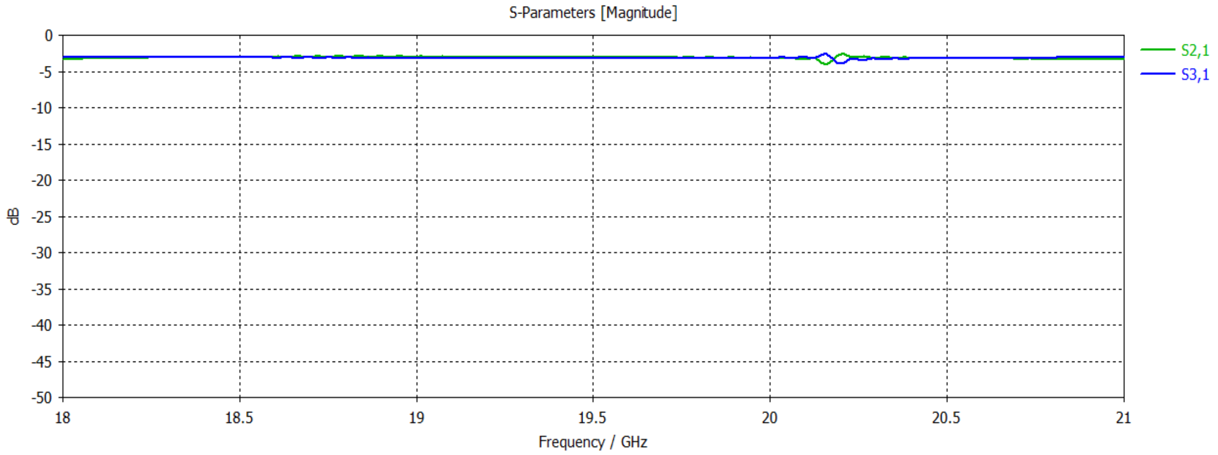
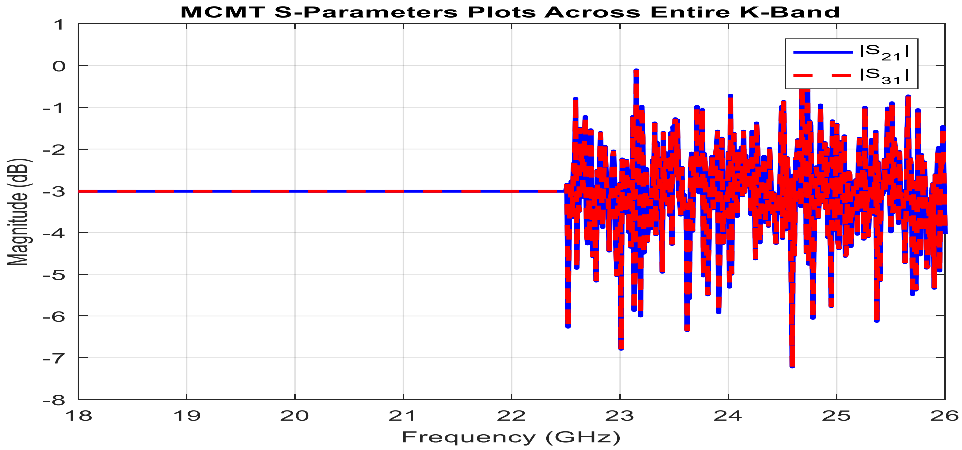


Figure 3: Simulated S_{21} (green) and S_{31} (blue) magnitudes' plots for Equal power division range

One of the most significant features of the proposed structure is the region between 18 and 21 GHz, where the proposed designed structure exhibits near equal-power distribution between the two output ports, represented by S_{21} and S_{31}. In this interval, both transmission curves converge and maintain a similar magnitude, indicating that the energy feed at the input port is divided almost equally between the two output ports.



The CST and MATLAB generated graphs show good agreement within the selected frequency band. Both results follow a similar trend in equal power division range of frequencies, indicating consistent system behavior.

Band	Plane	Method	Usable / Stable Frequency Region	Power Division Behavior (S21 & S31)	Dominant Physical Cause	Overall Performance Assessment
K (18–26 GHz)	H-plane	Simulation	18–21.5 GHz	Balanced at low band; imbalance near resonance	Higher-order mode excitation, energy redirection	Frequency-selective, unequal distribution near mid-band
		MCMT	Up to ~22.5 GHz	$S_{21} = S_{31}$, showing ideal power division; divergence at higher frequencies	Ripples due to neglect of higher-order modes, radiation, and losses	Good agreement at low–mid band; reduced accuracy at high band

Table 4.1 Comparison of Simulated and MCMT Results for Folded H-Palne Waveguide Power Divider/Combiner for K-Band

4.2 Far-Field Radiation Characteristics

The radiation pattern obtained from the CST far-field monitor [14] was studied to understand how the folded configuration affects electromagnetic behaviour at K-band frequencies. The plot shows that radiation is mainly directed along the axis of energy propagation, which indicates that the folding of the structure does not disturb the forward transmission of power.

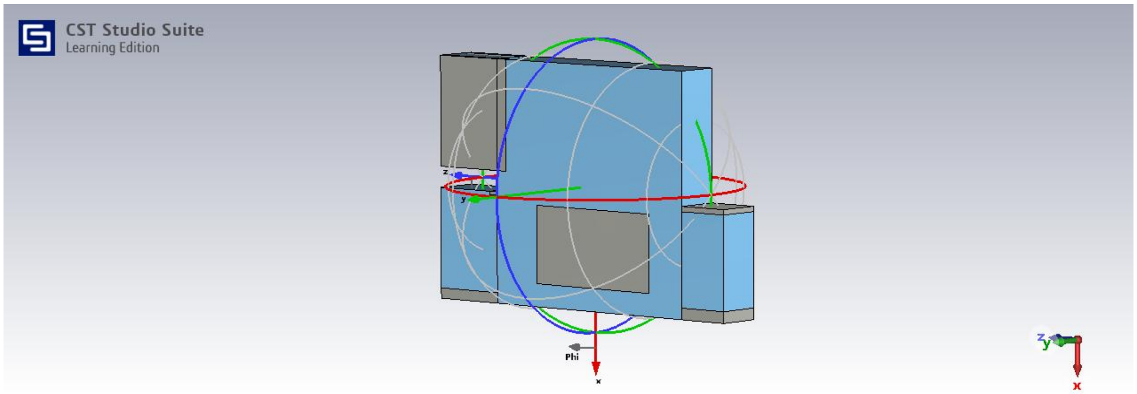


Figure 4: Far-Field Radiation Characteristics

When you look at the structure from angles the pattern looks the same. This means that the paths inside the structure add about the amount to the field that is sent out. The way the structure works shows that the folded parts are balanced and do not cause any problems with the timing. In folded shapes being, out of balance can distort the pattern but that does not happen with this structure. The folded parts of the structure are balanced. That is why the pattern stays the same.

In the direction of elevation, the radiation is confined in a small angular area, and all lobes are significantly desired [13, 14]. This means that the structure mostly works in its main mode within the defined range of frequencies. The lack of irregular radiation patterns further indicates that the folding mechanism does not appreciably stimulate higher-order modes.

As a result of the far-field response that was seen, it is possible to draw the conclusion that the folded K-band structure that was proposed maintains steady radiation behavior while simultaneously achieving compactness. It is especially helpful for waveguide-based components, which require a reduction in their physical size without compromising their electromagnetic performance, because this trait is highly valuable.

IV. APPLICATION POTENTIAL

The analyzed structure demonstrates behavior suitable for several microwave functions:

- Compact K-band bandstop or multiband filter
- Selective coupler or energy-diverting component
- Resonant cavity element in phased-array modules
- Microwave sensing structures requiring narrow notches

The ability to produce deep notches, controllable passbands, and multiple transmission paths within a small footprint makes this design useful for integration in next-generation front-end architectures.

V. CONCLUSION

CST Microwave Studio was utilised in order to design and simulate a folded K-band electromagnetic structure. When we combine asymmetric dielectric loading with metallic barriers, we get a wide range of resonant modes that have a big effect on the responses of S_{21} and S_{31} resonances. The design shows deep resonances between 22–23.6 GHz, moderate passband behaviour in the 24–26 GHz range, equal power division between 18-21 GHz. These properties show that it could be used in K-band filtering, coupling, division and recoil cavity applications.

VII. FUTURE SCOPE

This research, "Designing and Analysis of H- Plane Folded Waveguide Power Combiner for K-Band" holds significant potential for future research, particularly in the fields of microwave engineering, telecommunications, and RF (Radio Frequency) applications. Here are several potential directions and ideas that could shape the future scope of this research paper:

- Advanced Manufacturing Techniques for Fabrication
- Optimization of Power Combiner Design for Different Frequency Bands
- Integration with Other Components in Microwave Systems
- Efficiency Improvement and Loss Reduction
- Non-Linear and High Power Applications

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