High Power Dual Mode Single Tube Rotary Joint for Microwave Frequencies

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Abstract:

This paper describes a design for a dual channel radio-frequency (RF) rotary joint which is easy to manufacture and capable of handling high peak and average power. The rotary joint is based on a circular waveguide with the ability to transmit two RF channels via one physical channel. To get the best results for bandwidth and reflection several mode converters are investigated.

Key Words: Rotary joint, mode transition, high power

I. INTRODUCTION

Radar rotary joints act as transition gears between a transmitter/receiver and a rotatingantenna. The task of arotary joint is to provide a transmission path (a so called channel)between a rotating part and a static part.Waveguide rotary joints are commonly usedfor high radio-frequency (RF) power levels.

The basicoperating principle of a RF transmission channelis illustrated schematically in figure 1.

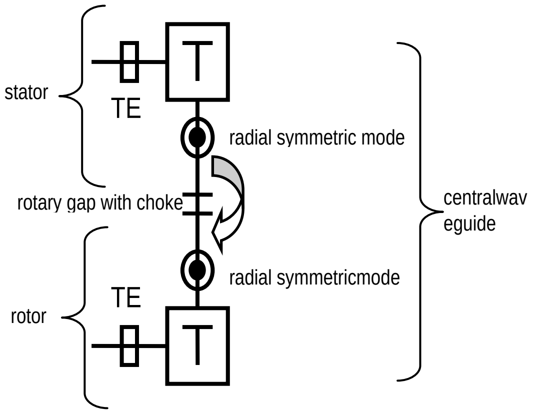

Figure 1: Schematic representation of a waveguide rotary joint

Theradar signal is transmitted in the fundamental mode TE_{10} via the rectangular waveguide.A transition converts theTE_{10} into a radially symmetric mode which propagates into the central waveguide.The central waveguide contains the rotary gap. A choke system at this position makes sure that no RF leaks out of the rotary joint.

The requirements for a RF rotary joint are very highin order to reduce its influence on the performance of a radar system. Especially the values for insertion loss within the relevant frequency band need to be as low as possible in order to increase the stability and efficiency factor of a radar system.

Furthermore it has to be guaranteed that there are no breakdowns due to high electrical field strengths. Higher frequencies means smaller structures and a reduced withstand voltage.

Additionally, operation at high altitude is critical as the decreased air pressure lowers the maximum power capability. For example an altitude of 15 km reduces the peak power capability of a RF system down to 2 percent compared to sea level[1]. Due to the diminishing heat convection at higher altitudes the average power suffers as well.

This issue becomes even greater once operation inaerospace is necessary. Because of the lack of convection the RF system will heat up very fast.

Furthermore while the primary breakdown for RF power is related to [1] extremely high, the secondary mechanism multipactionbecomes the dominating effect. Multipaction threshold is dependent on the frequency gap product,which means small gaps inside the structure may cause corona-like discharges.

To get the best results at higher frequencies waveguides are more suitable than coaxial structures. They are characterized by low loss transmission, can handle high peak power levels, and have an acceptable bandwidth which can be improved by using ridged waveguides.

II. SELECTION OF THECENTRAL WAVEGUIDE

The conventional design for waveguide rotary joints uses a transition from the rectangular waveguide TE_{10} mode to the radially symmetrical coaxial TEM mode[2]. At frequencies above 40 GHz a coaxial line can be the bottleneck of a system due to small gaps and high insertion loss.Thus a different approach is needed. A circular waveguide is the preferred choice,since insertion loss is lower and power capability is higher than in the rectangular waveguide (let alone coaxial systems).The central waveguidewould no longer be the limiting element of a rotary join.

There are more advantages of a circular waveguide rotary joint than just insertion loss and power handling. Due to the orthogonality of the different modes within a waveguide it is possible to send more RF channels over a singlephysical channel. This has big benefits in cost effectiveness for parts production and assembly. Dual channel transmission by a coaxial channel requires a bore hole in the inner conductor. A choke system transforms the inner conductor of the first channel to the outer conductor of the second one. For high frequencies these structures become very small and vulnerable to production uncertainties.

The main challenge of a circular waveguide rotary joints is the design of the mode transition. For the transmission channel a radially symmetric field is required to ensure that there is no performance dependency on the angle position of the antenna. The first two modes with this attribute in a circular waveguide are the TM$_{01}$ and the TE$_{01}$ mode. Since the propagation of a certain field is related to the diameter of the waveguide, it is inevitable that unwanted modes will propagate as well.

There is also a possibility to design a circular polarized channel with good results for the fundamental mode TE$_{11}$. The disadvantage of a 360 degree phase variation (linear dependency on the azimuthal position of the antenna) makes it unsuitable for most radar and antenna measurement applications. This approach will not be investigated further in this paper for this reason.

The excitation of unwanted modes leads to dispersion and resonances within the rotary joint. Thecause of the resonances is a mismatch of the different polarizations of the non-radially symmetric fields. Summed up, the transition of a rectangular to a circular waveguide needs to excite the targeted mode as pure as possible.

The demand of mode purity limits the bandwidth of a transition. Experience with circular waveguide rotary joints shows that a mode suppression of at least 30 dB in the transition is necessary. This is one of the main design criteria this paper has a deeper look into.

III.DESIGN OF THE TE$_{01}$TRANSITION

The biggest advantage, beside the low insertion loss, of using the TE$_{01}$ mode is that no choke between rotor and stator is necessary.

Since at least four other modes can propagate together with the TE$_{01}$ mode inside the circular waveguide, the transition has to be designed very carefully.

[3]describes the design of a “wrap-around” mode converter. The power in the rectangular waveguide is split in the E-plane into two branches. These branches split again and slot into the circular waveguide.To ensure an equal phase at every slot, the second split happens after a full wavelength is reached. The E-plane of the slots needs to be orthogonal to the axis of the circular waveguide to excite the TE$_{01}$ mode of the circular waveguide (Figure 2).

A disadvantage of the design is the dependency on the wavelength which decreases the bandwidth.

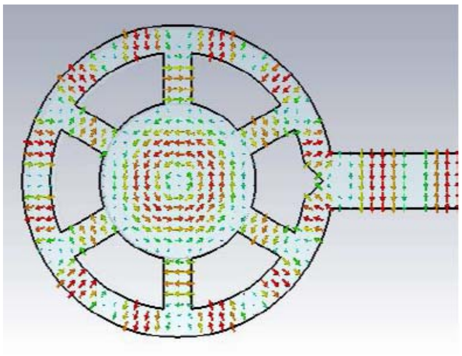

Figure 2: Cross section of a wrap-around mode converter

The most important part is the suppression of the unwanted modes. This is the main criterion if a transition is suitable for a rotary joint, since it has a massive influence on return loss and variation.

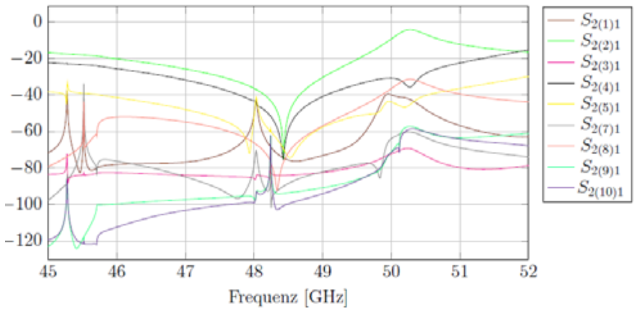

Figure 3: Unwanted mode decoupling of the wrap-around converter

Figure 2 shows the magnitude of S$_{21}$ Parameter for the different modes. Every mode and every polarization has an extra number in brackets. For example the missing (because desired) TE$_{01}$mode with only one polarizationwould be written as S$_{2(6)1}$.

As a result the 30 dB decoupling of the other modes are only reached over a small frequency band.

Another approach is given by [4]. This patent describes a transition for an overmoded coaxial rotary joint. It is realized by a double power splitter. A short in the end of the splitter grants an inductive coupling to a coaxial line. [5]created a first model of thisidea for a rectangular waveguide.

The combination of these two designs is shown in figure 4.

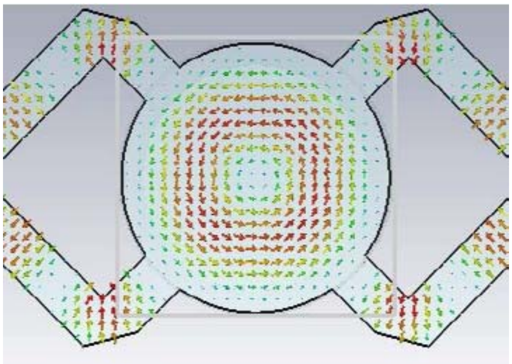

Figure 4: Cross section of a double power splitter mode converter

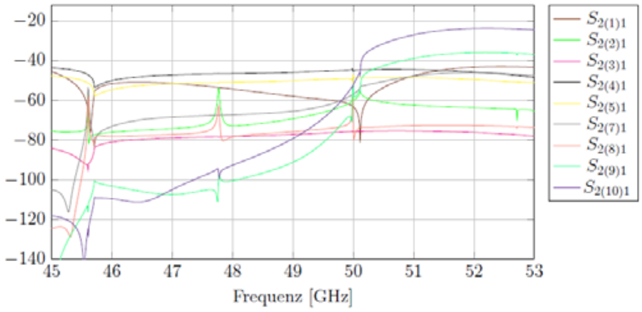

Figure 5: Decoupling of unwanted modes of the double power splitter mode converter

The suppression of the modes show the possible bandwidth of the transition reaches roughly 10% (Figure 5).

To get the best return loss the bends need to be as smooth as possible. This leads to the main disadvantage of the design: The outer dimensions of the rotary joint are quite large compared to the circular waveguide diameter.

Both transitions are easy to produce since they can be milled. Because of the bigger bandwidth the double power splitter mode converter is chosen for further investigation. Dimensions are not a problem for a prototype.

IV. DESIGN OF THE TM_{01}TRANSITION

The usage of the circular TM_{01}mode as central waveguide is not uncommon.[6]described a simple concept. The circular waveguide is arranged at a 90 degrees angle to the rectangular waveguide as shown in Figure 6. It is a direct mode conversion from the $TE_{10}$to TM_{10}.

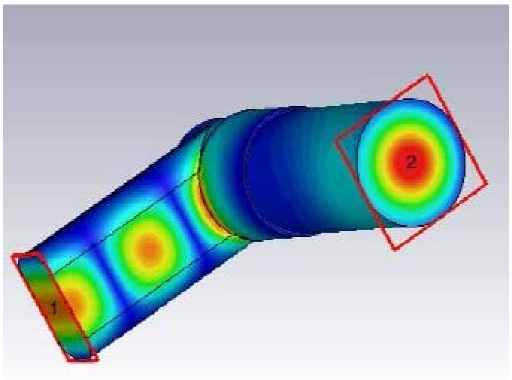

Figure 6: Simulationmodel ofthe direct TM_{01} mode converter

The disadvantage of this transition is the small bandwidth. While only one mode, the fundamental TE_{11}, has to be suppressed the next mode TE_{21}limits the usage of higher frequencies.

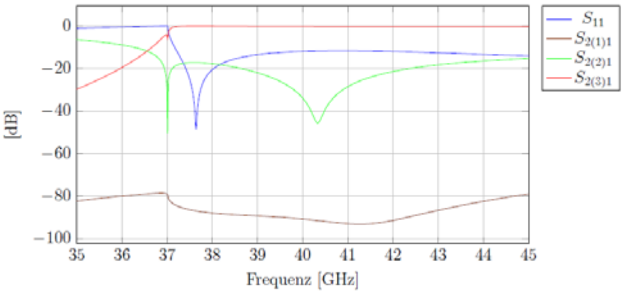

Figure 7: Reflection (S_{11}), undesired modes and polarizations ($S_{2(1)1}$, $S_{2(2)1}$) and transmission of the desired mode ($S_{2(3)1}$) of the direct TM_{01} mode converter

Figure 7 shows only about 2% relative bandwidth can be achieved with 30 dB mode suppression. This is important to minimize the dependency on the mechanical length of the channel.

Another idea is given by [7].

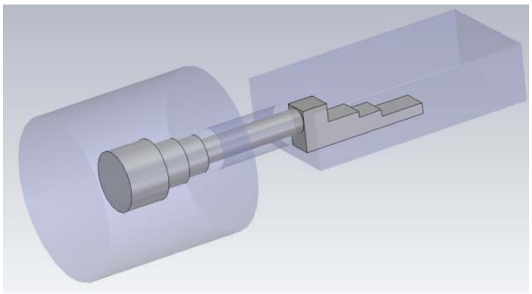

Figure 8: Mode transition rectangular waveguide to coax to circular

A transition to a coaxial line is necessary. While the values for average power and insertion loss are not critical due to the short coaxial part,the peak power remains a problem in this design.This is the reason for no further investigation.

Because of the low effort for the production, the direct TM_{01} mode converteris chosen for the prototype. The small bandwidth is enough to evaluate the influence on the TE_{01} channel.

V.DESIGN AND EVALUATION OF A TWO CHANNEL ROTARY JOINT

For the TM_{01} channel a central choke for circular waveguide is necessary. All components combined are shown in figure 9. The model is calculated withoutohmic losses to keep the simulation time low. Narrow-banded resonances occurring in figure 12 will flatten out in the prototype measurement due to the insertion loss.

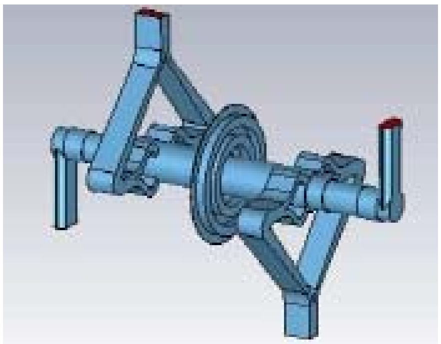

Figure 9: Simulation model of the rotary joint

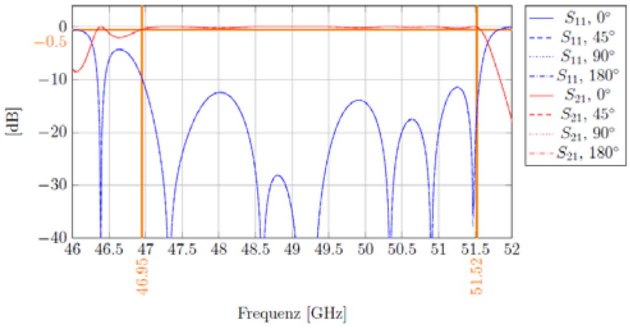

Figure 10: Simulated return and insertion loss over four rotation anglesof the TE_{01} channel

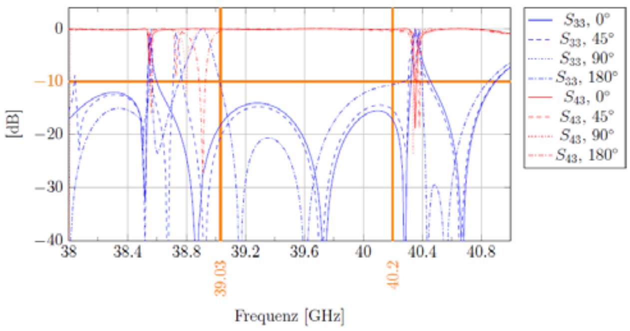

Figure 11: Simulated return and insertion loss over four rotation angles of the TM_{01} channel

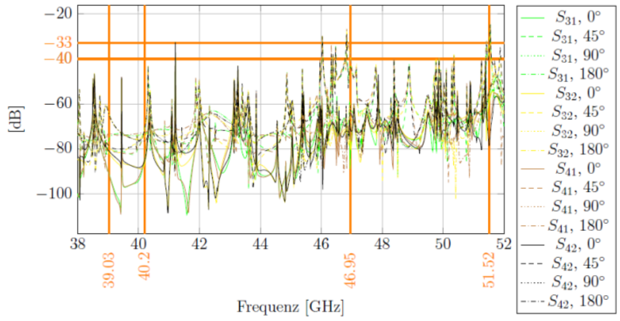

Figure 12: Simulated crosstalk over rotation between the two channels.

The following figuresshow theresults of the prototype. The measurements are very close to the simulated values. Outstanding is the extremely low insertion loss variation over rotation of the TE_{01} channel (Figure 14). As simulated the decoupling of the two channels reaches roughly 30 dB (Figure 16).

Figure 13: Pictures of the prototype

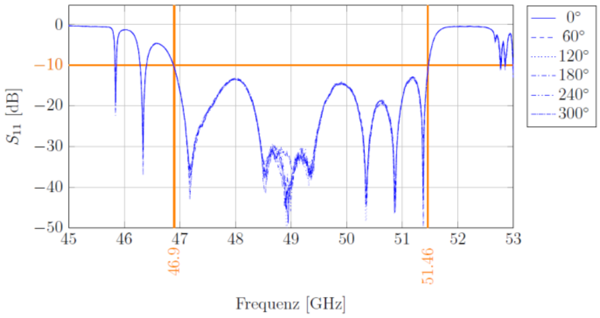

Figure 14: The measured return loss of the prototype´s TE_{01}over rotation.

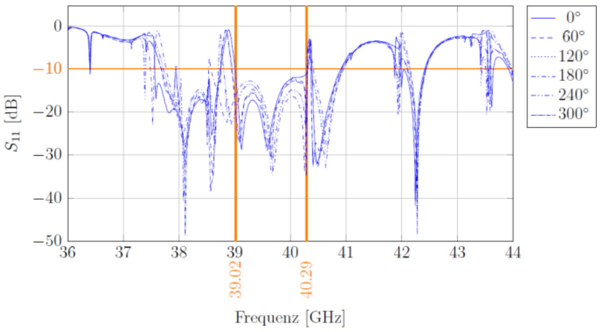

Figure 15: Return Loss over rotation measurement of the prototype´s TM_{01} channel.

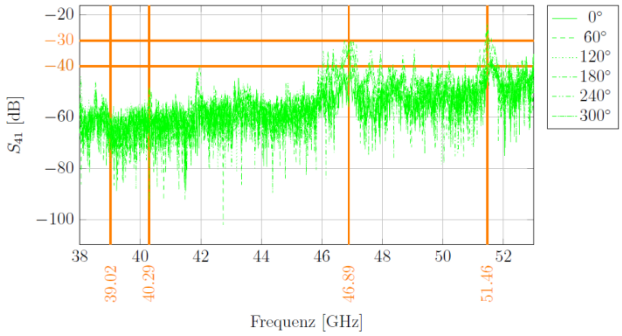

Figure 16: The crosstalk measurement with the isolation values over rotation

VI CONCLUSION

The measurements confirm the simulation results. A dual channel rotary joint for high power at frequencies above 40 GHz is realizable.

Although the frequencies are high, the design and fabrication of the rotary joint is very simple. Onlysimple turning and milling parts with relatively high tolerances guarantee a low cost of the device.

The channel decoupling of roughly 30 dB is sufficient for a lot of applications. Properly designed waveguide filters would eventually increase this value.

The insertion loss of the rotary joint is, due to the circular waveguides, lower than the loss of a rectangular waveguide. The reflection loss can be adjusted by modifying the transitions with apertures for example.

Because of the low insertion loss the average power capability is very high. The limiting factor is the operating temperature of the ball bearingsince the assembly doesn´t need any soldering.

The peak power capability of the rotary joint is increased as well. The larger gaps compared to a coaxial central waveguide make itmore suitable for high power and multipaction applications.

On the downside the two channels of the rotary joint need to be on close frequency to make sure that both modes are propagating.

VII SUMMARY

An approach for a single tube, dual RF-channel rotary joint is given. Important design criterion was the capability to transmit a high peak and average power.

Conventional rotary joints use coaxial lines as the central waveguide to guarantee more channels. At frequencies above 40 GHz the necessary dimensions are very small. This was spotted as the bottle neck for the power capability. In this paper we suggested a circular waveguide as central channel as a solution. Due to the mode orthogonality more RF-channels can be sent over one mechanical channel.

The mode transition was explained as the crucial part for this kind of system. To get the best results several mode converters were investigated. Two designs were chosen for experimental evaluation.

The measurements of the prototype confirmed the simulation results. Even at high frequencies, a high power dual mode single tube rotary joint can be realized at comparatively low costs.

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Bernhard Rimsl was educated at the University of Applied Science in Rosenheim, Germany as electrical and information technology engineer where he received his degree in 2012. Since 2011 he is employed at SPINNER in the RF design department for high power components and rotary joints.