Chapter 6

Mode Transducers for Circularly Symmetric Modes

The mode transducers presented in Chapters 3-5 are based on excitation of non-axis-symmetric TE_{1n} and TM_{1n} modes in circular waveguide. This chapter presents excitation of higher-order axis-symmetric modes such as TM_{01} and TE_{01} in circular waveguide. Simulation, modal analysis and design of the mode transducers to excite TM_{01} and TE_{01} modes in circular waveguide from rectangular waveguide TE_{10} mode have been carried out. The modal power in the desired modes have been maximized with very negligible power in the undesired modes by properly configuring the mode transducer geometry and optimizing the electrical performance in terms of return loss and insertion loss. The circular waveguide cross-sectional dimension is chosen so as to support both the TM_{01} and TE_{01} modes. The optimization of electrical parameters for the mode transducer of one channel has been carried out in the presence of the mode transducer of the other channel. Simulated and measured data on the RF performance of the rotary joint have been presented with rotation.

6.1 Excitation of TM_{01} Mode in the Circular Waveguide

The mode configuration of TM_{01} mode in circular waveguide is shown in Figure 6.1. This mode is generally excited in a circular wave guide using a coaxial probe, although there are other mechanisms of excitation also.
The requirement of rotary joint output ports to be rectangular waveguide makes the design of transitions from rectangular-to-coaxial-to-circular waveguide very complex and challenging. The following sections elaborate the methods to realize this mode transducer transition.

Figure 6.2 shows a mode transducer to excite TM01 mode in a circular waveguide from a rectangular waveguide propagating the dominant TE10 mode. This mode transducer consists of a door-knob transition in which a central coaxial rod protrudes in the circular waveguide from a rectangular waveguide. This method is selected because this coaxial rod can produce only radial and longitudinal electrical field components. In other words, it can produce only the transverse magnetic field components and cannot excite any of the undesired modes. The impedance offered to the coaxial probe is transformed by the doorknob at the interface of rectangular and circular waveguide to that of rectangular waveguide. A short is provided in the rectangular waveguide at a distance of quarter guide wavelength and fine tuning is carried out by changing the location of the short. In this configuration the axis of circular waveguide is kept perpendicular to the axis of
rectangular waveguide from which the coaxial probe protrudes in the circular waveguide to excite the mode.

The analysis and design has been presented in Ku-band with center frequency of 13.7 GHz. The diameter of the circular waveguide has been selected as 34 mm which is oversized for TM01 so as to supports the next higher order circular symmetric mode TE01 mode to realize finally a dual channel rotary joint at Ku-band. This diameter will also support the undesired modes TE11, TE21 and TM11 in circular waveguide along with the desired mode TM01. Thus, TM01 mode has to be excited with minimum power transfer in the supported undesired modes TE11, TE21 and TM11.

WR-75 rectangular waveguide (19 mm X 9.5 mm) has been used as input port of the mode transducer. The length of circular waveguide is taken as 175 mm. The computed guide wavelength for TM01 mode in the circular waveguide is 25 mm. The diameter of the coaxial probe is selected as 3.3 mm. The length of the coaxial section from which the probe protrudes in the circular waveguide is taken 3.2 mm. The doorknob transformer and length of the axial probe is optimized for maximum coupling of power in the desired TM01 mode and rejection of higher order modes. The optimized probe length which gives the required return loss and power coupling is 16.5 mm. The doorknob is modeled using HFSS in the form of an incremental step transformer which follows the profile of a semi-sphere section of radius 5.2 mm. The optimized plunger/short distance in the rectangular waveguide which gives optimum return loss is 19.65 mm. The cross-sectional dimension of the coaxial section between rectangular and circular waveguide has been designed so as to support only TEM mode.
Figure 6.2 Schematic of TM$_{01}$ mode transducer.

The modal amplitude was computed for various modes to see the mode purity of the TM$_{01}$ mode and the rejection of the other modes. The results of the analysis are shown in Figure 6.3. From Figure 6.3, it is clear that most of the power is confined in the TM$_{01}$ mode and rejection of other higher order modes is better than -22 dB.

Figure 6.3 The simulated modal amplitudes for different modes in the circular waveguide for TM$_{01}$ mode excitation.
Two mode transducers of Figure 6.2 were put back to back in order to realize a rotary joint (see Figure 6.4). This rotary joint [95] geometry was modeled on HFSS to predict return loss, insertion loss performance and their variation with 360 degree rotation of the movable part with respect to the fixed part of the joint.

![Rotating Joint Image](image)

Figure 6.4 Single channel rotary joint with doorknob transition for TM_{01} mode excitation in the circular waveguide.

The simulated insertion loss and return loss performance with rotation of the single channel rotary joint is shown in Figure 6.5 and Figure 6.6, respectively.

![Insertion Loss Graph](image)

Figure 6.5 Simulated insertion loss of the single-channel rotary joint with rotation.
Figure 6.6  Simulated return loss of the single-channel rotary joint with rotation.

The measured return loss and insertion loss have been presented for rotation of 0, 90, 180 and 270 degrees as shown in Figures 6.7 and 6.8 respectively.

Figure 6.7  Measured return loss of the single-channel rotary joint with rotation.
The schematic of the other possible configuration of $\text{TM}_{01}$ mode exciter is shown in Figure 6.9. In this configuration rectangular waveguide axis and circular waveguide axis are oriented in the same direction unlike the previous configuration of doorknob transition in which both waveguide's axes are transverse.

Figure 6.9  Rectangular to circular waveguide transition for exciting $\text{TM}_{01}$ mode in circular waveguide.
6.2 Excitation of TE₀₁ Mode in the Circular Waveguide

Figure 6.10  (a) Field configuration of TE₀₁ mode in circular waveguide. (b) Scheme of TE₀₁ mode excitation in circular waveguide using four slots.

The next higher order circularly symmetrical mode in a circular waveguide is TE₀₁ mode which may be used for realizing single or dual-channel rotary joints. The modal configuration of TE₀₁ mode is shown in Figure 6.10(a).

Since, the TE₀₁ mode of a circular waveguide is a higher-order mode, the size of the waveguide selected to support this mode will automatically support four lower-order modes which are TE₁₁, TM₀₁, TE₂₁, TM₁₁, respectively. In the Section 2.4 of Chapter 2, the simulation of a slot coupled oversized circular waveguide showed that sufficient power couples in the lower-order modes along with the desired circularly symmetrical higher-order TE₀₁ mode. It was also shown that the lower-order modes can be suppressed and the purity of the TE₀₁ mode can be achieved by using four slots. Any unbalance in
the excitation of the slots may excite undesired lower order modes and the presence of these modes may not allow to achieve the goal of uninterrupted transmission of power with rotation in rotary joints.

In order to excite pure TE$_{01}$ mode, schematic of the transition described in [68] as shown in Figure 6.11(b) may be used. However, in [68] the exact philosophy of excitation of the four slots with equal amplitude and phase is not very much clear. In order to study and prove the concept of TE$_{01}$ mode excitation in a circular waveguide using four slots on its periphery, the schematic of Figure 6.11 (a) may be used in which a four way equal power divider is used to couple power in TE$_{01}$ mode of circular waveguide through the 4 axial slots.

![Figure 6.11](image)

(a) (b)

Figure 6.11  TE$_{01}$ mode excitation in the circular waveguide using (a) 4-way power divider. (b) Ring waveguide surrounding circular waveguide.

A proof of conceptual model of a dual channel rotary joint has been designed and realized using the configurations of Figure 6.11(a) to excite TE$_{01}$ mode and Figure 6.9 for TM$_{01}$ mode.
For TE$_{01}$ mode excitation, a 4-way power divider which yields four equal amplitude and phase output signals was realized using WR-75 waveguide. The amplitude and phase imbalance over 1.0 GHz bandwidth was ± 0.25 dB and ± 5° dB respectively.

A circular waveguide of diameter 31.5 mm and fed through 4 slots by the four-way power divider has been modeled and simulated on HFSS. The location of the short position in the circular waveguide from center of the slots and slot dimensions are optimized to couple maximum power in the TE$_{01}$ mode in circular waveguide. The optimized slot length and width are 11.5 mm and 2 mm respectively, the position of the short (end walls of the circular waveguide) with respect to slot is 9.35 mm.

The simulated modal amplitudes for different modes show that the maximum power is confined in the TE$_{01}$ mode and the rejection for other undesired modes is better than 30 dB. Simulated return loss (-17 dB) bandwidth is 125 MHz for this transducer.

The other configuration as shown in Figure 6.11(b) to excite TE$_{01}$ mode in circular waveguide through 4-slots from ring rectangular waveguide was also modeled and simulated on HFFS. The diameter, slot dimension and short locations of the circular waveguide were optimized for balanced excitation of the four slots to couple four slots. The optimized diameter of the circular waveguide is 30.6 mm. The optimized slot length is 10 mm and width is 1.5 mm. The slot thickness is 2 mm. Its location from the input end wall of the circular waveguide (from the short) is 10.9 mm. A triangular cone was used at the periphery of the circular waveguide at the output location for impedance matching. The height of the cone is 9.7 mm, length is 6.5 mm and the length of the base of the cone around the periphery is 9 mm. The simulated modal amplitudes for different modes in the circular waveguide for this configuration show that the maximum power is confined in the TE$_{01}$ mode and the rejection for other non desired modes is better than 30 dB.
6.3 Excitation of TM$_{01}$ and TE$_{01}$ Modes in a Common Circular Waveguide to Realize a Dual-channel Rotary Joint

The individual mode transducers to excite TM$_{01}$ and TE$_{01}$ modes in circular waveguide from rectangular waveguide TE$_{10}$ were presented separately in Sections (6.1) and (6.2) respectively. The two types of mode transducers shown in Figure 6.9 and Figure 6.11(a) are combined to design a dual-channel rotary joint. Therefore, modal analysis has been carried out for the configuration which incorporates both the transducers to excite TM$_{01}$ and TE$_{01}$ modes in a common circular waveguide. Two common modes transducer to excite TM$_{01}$ and TE$_{01}$ modes, placed back-to-back with an air gap may be utilized to realize a dual channel rotary joint having choke joint and bearing mechanism.

The dual channel rotary joint was simulated on HFSS to compute return loss, isolation between two channels and power coupled to the required modes. Simulated results show that the maximum power is coupled in the TM$_{01}$ and TE$_{01}$ modes. A rejection better than 60 dB is obtained for non desired modes for TM$_{01}$ channel and better than 30 dB for TE$_{01}$ channel at 13.5 GHz.

The photograph of the dual channel rotary joint [96] is shown in Figure 6.12.

![Figure 6.12 The photograph of the dual channel rotary joint.](image-url)
The measured return loss and insertion loss of the channel-1 (TM$_{01}$ channel) is shown in Figure 6.13(a) and in Figure 6.13(b), respectively.

![Figure 6.13 (a) Measured return loss at the input port of channel-1 (TM$_{01}$ channel).](image)

The measured return loss and insertion loss of the channel-2 (TE$_{01}$ channel) is shown in Figure 6.14(a) and in Figure 6.14(b) respectively. Measured isolation between channel-1 and channel-2 is shown in the Figure 6.15.

![Figure 6.13 (b) Measured insertion loss of channel-1 (TM$_{01}$ channel).](image)
Figure 6.14  (a) Measured return loss at the output port of channel-2 (TE$_{01}$ channel).

Figure 6.14  (b) Measured insertion loss of channel-2 (TE$_{01}$ channel).

Figure 6.15  Measured isolation between channel-1 and channel-2.
6.4 Compact Design of Dual Channel Rotary Joint

The configurations of Figure 6.9 for TM$_{01}$ mode excitation and Figure 6.11(b) for TE$_{01}$ mode excitation have been combined to design a compact dual channel waveguide rotary at Ku-band. Two such dual-mode transducers are placed back to back to develop a compact dual channel rotary joint as shown from its HFFS model in Figure 6.16.

![Figure 6.16 Solid model of the compact dual channel rotary joint with TM$_{01}$ and TE$_{01}$ mode excitation in the circular waveguide.](image)

In the presence of one channel the RF performance of the other channel has been simulated with different angular orientations of one part with respect to the other part of the rotary joint. The critical geometries of TM$_{01}$ and TE$_{01}$ mode transducers of the rotary joint have been optimized to achieve return loss better than 19 dB, insertion loss less than 0.1 dB and isolation between channels better than 40 dB with 360° rotation for minimum bandwidth of 50 MHz. Probe length, height and location of the step transformers have been optimized for TM$_{01}$ channel. Slot length and location of slots from the end walls of the circular waveguide have been optimized for TE$_{01}$ channel. The optimized slot length and width have been found to be 10 mm and 1.5 mm, respectively. The location of the slot from the end walls is 10.9 mm. A triangular cone is used at the periphery of the circular waveguide at the output location for impedance matching. Based on the RF design and simulation, a dual channel rotary joint was fabricated and tested. The simulated and measured performance of this compact dual-channel rotary joint are presented in the next section.
6.4.1 Simulated Results of Compact Dual-Channel Rotary Joint

The complete geometry of compact dual-channel rotary joint mode transducer was modeled on HFSS to compute the power coupled to various modes in the circular waveguide from rectangular waveguides to see the mode purity of TM$_{01}$ and TE$_{01}$ modes. The Figures 6.17(a) and 6.17(b) show the modal amplitude of fundamental and higher-order modes for the optimized mode transducers for TM$_{01}$ channel (channel-1) and TE$_{01}$ channel (channel-2), respectively. The Figures 6.17(a) and 6.17(b), show that the maximum power is coupled in the TM$_{01}$ and TE$_{01}$ modes in the circular waveguide and a rejection better than 30 dB is obtained for non-desired modes over the frequency band.

Figure 6.17 (a) Modal amplitudes of fundamental and higher order modes for the optimized mode transducer for channel-1 (TM$_{01}$ channel).

Figure 6.17 (b) Modal amplitudes of fundamental and higher order modes for the optimized mode transducer for channel-2 (TE$_{01}$ channel).
The simulated results for return loss, insertion loss and isolation between channels is presented in Figure 6.18(a). The orientation of rotary joint ports for which the simulation has been performed is shown in Figure 6.18(b). In this figure, the orientation between the rotor and the stator parts of rotary joint is assumed as zero degree. The performance has been optimized around the center frequency of 13.515 GHz. The simulated return loss performance is better than 19 dB over the desired bandwidth of 50 MHz i.e., from 13.49 to 13.54 GHz for both the channels of rotary joint. The simulated insertion loss is 0.1 dB over desired 50 MHz, 0.15 dB over 100 MHz, and 0.65 dB over 200 MHz as shown in the Figure 6.18(a). -17 dB return loss bandwidth around the center frequency is 100 MHz for TE_{01} Channel and 110 MHz for TM_{01} channel. The simulated isolation between both the channels is better than 68 dB.

Figure 6.18  
(a) The simulated return loss, insertion loss and isolation between two channels of dual-channel rotary joint.  
(b) The orientation of rotary joint ports. Here, i/p stands for input and o/p for output.
6.4.2 Simulated Performance with 360 degree Rotation:

Modeling and simulation has been performed to predict the electrical performance of the rotary joint when one half part is rotated with respect to the other half part. Initially, the performance with rotation is predicted for individual channels in the absence of the other channel. The return loss performance for 0°, 90°, 180° and 270° rotations of the rotating part of TM$_{01}$ channel in the absence of TE$_{01}$ channel is shown in Figure 6.19. Similarly, the return loss performance for 0°, 90°, 180° and 270° rotation of the rotating part of TE$_{01}$ channel in the absence of TM$_{01}$ channel is shown in Figure 6.20. It is seen that return loss performance is very stable for TM$_{01}$ channel with rotation but varies slightly for TE$_{01}$ channel with rotation.

![Figure 6.19](image1.png)  
Figure 6.19 The return loss performance of TM$_{01}$ channel in the absence of TE$_{01}$ channel.  

![Figure 6.20](image2.png)  
Figure 6.20 The return loss performance of TE$_{01}$ channel in the absence of TM$_{01}$ channel.

When both channels are present simultaneously, the return loss, insertion loss and isolation performance for 0°, 90°, 180° and 270° rotations of the rotating part with respect to stationary part is shown in Figure 6.21 for TM$_{01}$ and TE$_{01}$ channels. It is seen that in the presence of both TM$_{01}$ and TE$_{01}$ channels, electrical performance varies with rotation for both channels. But the simulated performance is within acceptable limits for both the channels.
Figure 6.21  Simulated performance with rotation in presence of both channels simultaneously.
(a) Insertion loss for TM$_{01}$ channel. (b) Insertion loss for TE$_{01}$ channel.
(c) Return loss for TM$_{01}$ channel. (d) Return loss for TE$_{01}$ channel.
(e) Isolation between TM$_{01}$ and TE$_{01}$ channels.
6.4.3 Measured Results of Compact Dual-channel Rotary Joint

Various parts of the compact rotary joint have been fabricated and assembled. Proper jigs, fixtures and dowels have been used to align coaxial probes protruding in the upper and lower half of the cylindrical cavity for TM$_{01}$ channel. An angular contact ball bearing has been assembled between upper and lower half of the cylindrical cavity for the implementation of rotation between fixed and rotating parts of the rotary joint. The measurement for the compact dual-channel rotary joint (see Figure 6.25) has been performed on a PNA series network analyzer (E 8363 B) for return loss, insertion loss and isolation between channels with respect to 360 degree rotation at the interval of 90 degree. The measured return loss and insertion loss with rotation is shown in Figure 6.22 for TM$_{01}$ channel and in Figure 6.23 for TE$_{01}$ channel. The isolation between channels with rotation is shown in Figure 6.24.

It is clearly seen from Figure 6.22(b) and Figure 6.33(b) that the measured variation of insertion loss is within ±0.1 dB with rotation at the edge of the frequency band and it is within ±0.05 dB near the center frequency at 13.515 GHz. The return loss performance is nearly 17 dB for TM$_{01}$ channel and better than 15.6 dB for TE$_{01}$ channel over 50 MHz bandwidth. The isolation between channels is better than 39 dB over the frequency band. The nature of measured electrical performance is similar to the simulated results, except slight shift of resonance frequency. Various plots show that the purity of excited circular symmetric modes has been achieved which was the main objective of the design of rotary joint. The slight deviation in the values of return loss and isolation from simulated results could be attributed to achieved fabrication tolerance and assembly and alignment errors.
Figure 6.22 Measured performance of the compact dual channel rotary joint.
(a) Return loss at the input port of channel-1 (TM$_{01}$ channel).
(b) Measured insertion loss of channel-1 (TM$_{01}$ channel).

Figure 6.23 Measured performance of the compact dual-channel rotary joint.
(a) Return loss at the input port of channel-2 (TE$_{01}$ channel).
(b) Measured insertion loss of channel-2 (TE$_{01}$ channel).
Figure 6.24  Measured isolation between channel-1 and channel-2 for the compact dual-channel rotary joint.

The photograph of the compact dual channel rotary joint is shown in Figure 6.25.

Figure 6.25  The photograph of the compact dual-channel rotary joint.
6.5 Conclusion

The mode transducers to excite TM$_{01}$ and TE$_{01}$ modes in a circular waveguide have been presented in this chapter. This investigation finally led to the development of a compact dual channel rotary joint. The measured results of the compact dual channel rotary joint closely meets the requirement of insertion loss, isolation and return loss parameters with 360 degree rotation. This rotary joint has been successfully developed as flight model to be used for the scan mechanism of pencil beam scanning scatterometer antenna for Oceansat-2 mission which is aimed for remote sensing applications. The developed flight model rotary joint as shown in Figure 6.26 meets the specifications of insertion loss, return loss and isolation of 0.35 dB, -19 dB and 40 dB respectively with 360 degree rotation. The measured results of the rotary joints presented in this chapter are in close agreement with the simulated results for most of the configurations. Slight deviations for a few configurations may be attributed to fabrication and assembly errors, as the devices were not fabricated as a single piece but in different pieces due to their complex configurations.

![Image of compact dual-channel rotary joint](image)

Figure 6.26 The photograph of the compact dual-channel rotary joint (flight model).