A WR-15 High-Power Handling, Amplitude and Phase Stable Full Band Rotary Joint Based on TE01 Mode

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***Abstract* — A new type of U-style, high-power handling, amplitude and phase stable, WR-15 waveguide rotary joint is designed and built utilizing TE_{01} mode transmission. The joint has excellent phase and amplitude stability over the full WR-15 waveguide bandwidth and exhibits a typical phase variation of ±1.0 degrees and amplitude variation of ±0.1 dB through a complete 360-degree rotation. The electrical and mechanical design is scalable to sub-THz frequencies as high as 170 GHz and can be configured to create L-Style and I-Style type rotary joints.**

***Keywords* — Millimeter-wave, Sub-THz, Waveguide, rotary joint, TE_{01} mode, High power handling, WR-15.**

I. Introduction

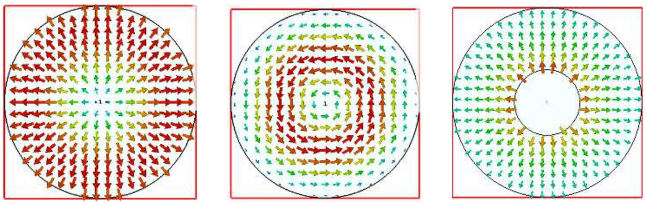
In radar scanning, two methods are commonly employed. One type is electronic scanning, which achieves beam scanning by controlling the phase of the array antenna. However, this type of radar system is complex and costly. The other method, which is more widely used, is mechanical scanning, in which the antenna and transceiver are connected by a common rotary joint. The antenna is attached to the rotating part, or rotor, and the transceiver is attached to the stationary part, or stator, of the rotary joint. A servo motor drives the antenna rotation, while the transceiver function ensures static state, ultimately achieving beam scanning of the radar system.

As an energy transmission device in the microwave system, the rotary joint needs to maintain low insertion loss and return loss while also minimizing phase and amplitude variation during rotation. The currently available commercial microwave rotary joints can be roughly divided into coaxial and circular waveguide types. The core principle of design for both types is utilizing the symmetry of the electric field to propagate the RF signal through the rotary joint with minimal loss or variation. The coaxial type utilizes TEM mode [1], while the circular waveguide type can utilize TE_{01} and TM_{01} [2-6], as well as circular polarized signal [7]. The electric field of these modes is distributed axially symmetrically within the waveguide. The TEM mode utilizes a waveguide coaxial converter structure to excite the TEM mode, and then the inner and outer conductors form a coaxial cavity to transmit signals. The mechanical structure between the inner and outer conductors has a discontinuity due to the rotational gap, and a choke slot structure is commonly inserted at the gap to compensate. The TM_{01} mode or TE_{01} mode belongs to the higher-order mode of a circular waveguide and is generated through a higher-order mode transformer from rectangular waveguide to circular waveguide, and then transmitted through the circular waveguide. At present, TEM mode rotary joints which can achieve full waveguide band operation (40% bandwidth) typically operate below the millimeter-wave frequency bands. Due to the smaller wavelength in millimeter-wave and Sub-THz frequency bands, the mechanical features of a TEM mode based rotary joint must be made very small, such as the diameter of the inner conductor. This makes it difficult to manufacture and assemble, which results in reduced electrical performance stability, consistency, and service life. In addition, the small inner conductor coaxial structure limits the power handling of the rotary joint. In contrast, the TM_{01} and TE_{01} modes are more suitable for millimeter-wave and sub-THz applications since their signal transmission structures do not utilize the problematic inner conductors. However, the traditional conversion methods for the TM01 and TE01 mode have smaller bandwidth (5-10%) compared to TEM mode; most of the relevant research today for TM01 and TE01 mode based rotary joints are focused on narrow band operation.

In this paper a WR-15, U-style, waveguide rotary joint based on an improved TE_{01} mode transmission structure is designed, manufactured, and tested. The novel, broadband TE_{10} mode to TE_{01} mode transformer is designed to achieve full WR-15 waveguide band operation with exceptional phase and amplitude stability and higher power handling compared to TEM mode based rotary joints. The electrical and mechanical design is scalable to frequencies as high as 170 GHz and is adaptable to other rotary joint configurations such as L-Style and I-Style.

II. Concept Design and Simulation

The key to designing a rotary joint is ensuring the field distribution inside the cavity is not disrupted during rotation. This requires the use of axisymmetric field distributions, such as TEM mode, TE_{01} mode, and TM_{01} mode (see Fig.1); Meanwhile, due to the mechanical discontinuity caused by the rotational gap of the rotary joint, it is necessary to ensure that the gap does not affect electrical performance, which is often achieved using a choke slot structure. During the development of the WR-15 rotary joint, the TE_{01} mode was selected as the main transmission mode. The electric field distribution of this mode is represented by a circular ring distribution in the cross-section of the circular waveguide as shown in Fig. 1.



(a) (b) (c)

Fig. 1. Waveguide fields distribution : (a) TM_{01} mode; (b) TE_{01} mode; (c) TEM mode in coaxial structure

In prior reported work, a 1 to 4 power divider structure was used to feed four branches at the 0°, 90°, 180°, and 270° positional direction into the circular waveguide, ultimately forming a TE_{01} mode within the waveguide that can achieve a working bandwidth of 16.8% [8]. Due to the feeding network of the TE_{10} mode in four directions, this affects the uniformity of the mode within the circular waveguide, thereby limiting the operating bandwidth. Other designs used a 1 to 16 power divider to transmit TE_{01} mode within a coaxial cavity, but the working bandwidth achieved was only 10-19.9% [9-10]. For this novel WR-15 rotary joint design, a 1 to 8 power divider is used that feeds TE_{10} modes into the circular waveguide from eight directions (0°, 45°, 90°, 135°, 180°, 225°, 270°, and 315°), and matching impedance step transformers are added to complete the mode conversion. The TE_{01} conversion method employed here results in a more uniform field distribution than prior work and the working bandwidth is around 40%.

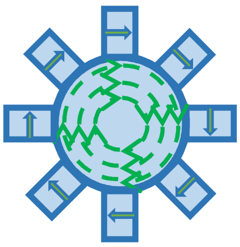
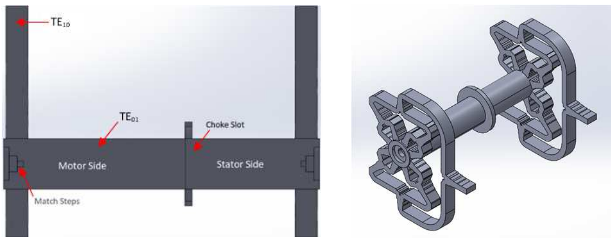


Fig. 2. A demonstration of a 1-to-8 power divider.



(a) (b)

Fig. 3. TE10 to TE01 converter: : (a) 2D layout; (b) 3D demonstration.

The size of the circular waveguide required for ensuring the transmission of TE_{01} mode is determined using the following formula:

$$r > P'_{01}/(2\pi/\lambda_c) \tag{1}$$

$$r > 3.66\ mm \tag{2}$$

Where r is the radius of the circular waveguide, P_{01} is the first root of the Bessel function J_0, where it is equal to 3.832, and λ_c is the cutoff frequency wavelength. Here, the wavelength corresponding to 50 GHz is selected. Finally, in consideration of the matching problem within the circular waveguide, r was ultimately chosen to be 4.295 mm.

After the size of the circular waveguide is determined, the eight coupling ports are evenly distributed around the circular waveguide, and then connected using a three-stage 1 to 8 power divider to form a mode converter from TE_{10} mode to TE_{01} mode. A cylindrical step structure was added to the ends of the circular waveguide to improve the impedance matching of the mode transition.

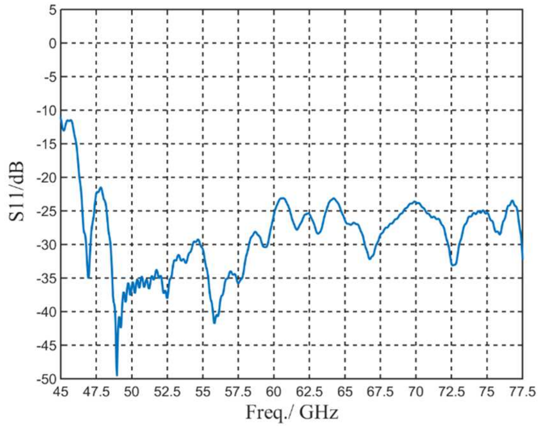


Fig. 4. Simulation, Return Loss, S_{11}

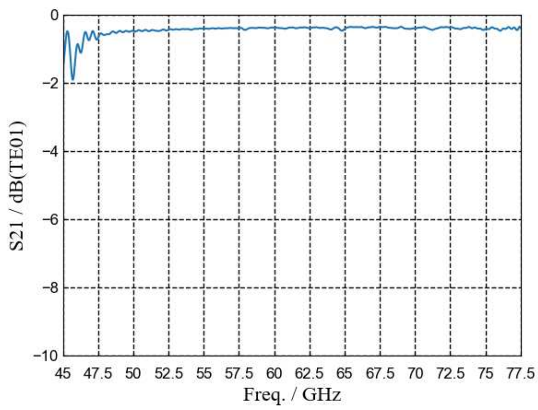


Fig. 5. Simulation, Insertion Loss, $S_{21}(TE_{01})$

Fig. 4 and Fig. 5 shows the simulated return loss/insertion loss of the rotary joint structure. From 50-75 GHz, S_{11} is around -25 dB typical and S_{21} is below -0.05 dB and the conversion efficiency from TE_{10} to TE_{01} mode is over 99.4%. At the same time, the energy ratios of the other propagating higher order modes within the circular waveguide were simulated (20 modes were observed here, only those with energies higher than -40 dB were given). The combined energy of other modes is below -30 dB, which shows that the currently designed structure is well suited to suppressing these other unwanted higher order modes.

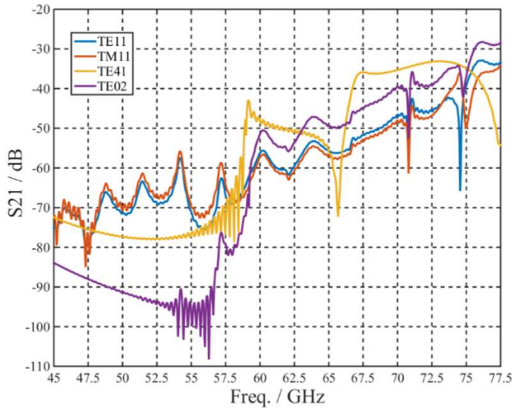


Fig. 6. Simulated S21 curves for the other modes

Using the mode converter as described in Fig. 3, a "U" style rotary joint is formed by connecting it back-to-back. Because the electric field intensity of TE_{01} mode in a circular waveguide approach zero at the centre and wall of the waveguide, this type of rotary joint is not sensitive to the size of the choke slot. If the gap is much smaller than the wavelength, the electrical performance will remain stable when the joint rotates.

III. Final Design Measured results

The rotary joint as described was manufactured, assembled, and tested on a WR-15 vector network analyzer. The mechanical design incorporates high precision ball bearings to provide the required concentricity and rotational stability. A mounting flange that allows the rotary joint to be panel mounted is added for user convenience. The results can be seen in Fig 8. and Fig 9. A total of five units were manufactured and tested. From 50-75 GHz, the measured return loss of the test units are better than -15 dB, and the measured insertion loss is about 1.2 dB typically. The return loss data collected is, on average, what was expected from the simulation data, while the measured insertion loss is noticeably worse than what was simulated. It is believed that this discrepancy is due to the machining imperfections of the waveguide sections. While the machining quality of the waveguides in these test units were reasonably good, this can be improved upon implementation of more advanced machining processes or adoption of a more detailed structure. In addition to that, to machine the waveguides, the structure must be split, and therefore there may be slight misalignments at different points throughout the structure. Therefore, some consideration must be given between how perfect a waveguide structure may be simulated as and what is practically achievable.

Fig. 7. WR-15 U-style rotary joint

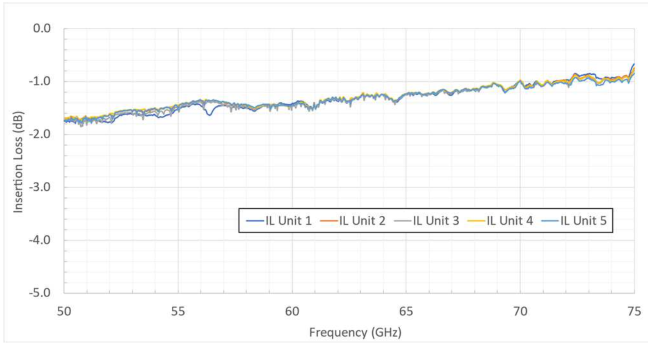


Fig. 8. Measured Insertion Loss

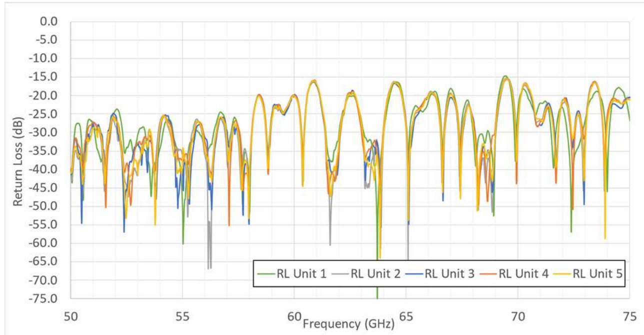


Fig. 9. Measured Return Loss

In addition, phase and amplitude variation measurements were also taken to characterize the electrical stability of the joint. Waveguide twists, E-plane and H-plane bends were used to create a test setup that allows two rotary joints to be connected such that the rotors can rotate while the stators remain fixed on the VNA extenders. In this way, the changes in phase and amplitude during rotation can be observed and measured easily.

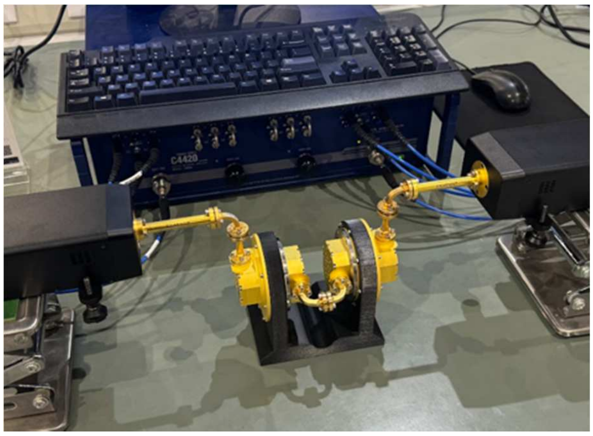


Fig. 10. Test setup for phase and amplitude stability measurements

The phase, insertion loss, and return loss were measured at the starting position (0°) of the rotary joints, and at 3 more angular positions 90° apart from one another (90°, 180°, 270°). The results are shown in Figures 11, 12, and 13. For a full 360° rotation of the rotary joint, the phase variation is within ±1.0°, the insertion loss variation is within ±0.1 dB, and the return loss varies by an average of 0.28 dB.

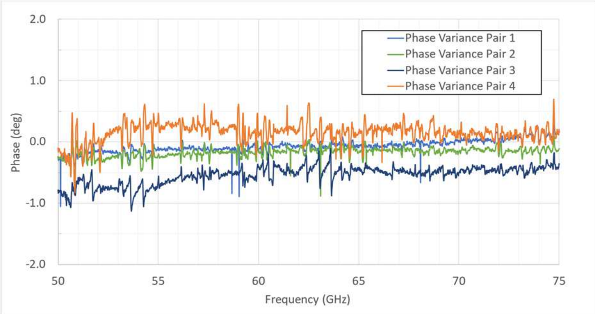


Fig. 11. Measured Phase Variation

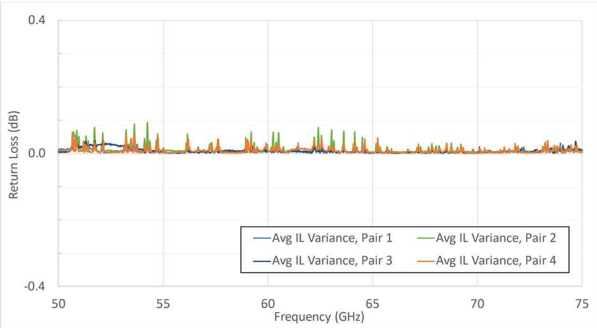


Fig. 12. Measured Insertion Loss Variation

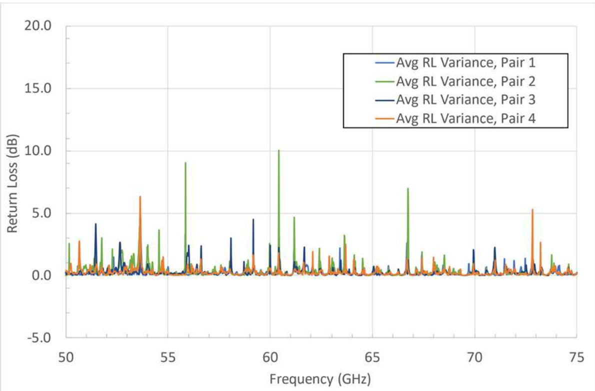


Fig 13. Measured Return Loss Variation

IV. Conclusion

A WR-15, U-style waveguide rotary joint based on a new, more efficient TE_{01} mode transmission structure was designed, built, and tested. The rotary joint displayed superb phase and amplitude stability over the entire WR-15 waveguide bandwidth with a typical phase variation of ±1.0 degrees and amplitude variation of ±0.1 dB through 360-degrees of rotation. This design offers higher power handling capacity than TEM mode rotary joints due to the lack of the inner conductor in the propagation structure. The electrical and mechanical design is easy to manufacture and scalable to sub-THz frequencies as high as 170 GHz and can be configured to create L-Style and I-Style type rotary joints as well.

Acknowledgment

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