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Ku band Rotary Joint Design for SNG Vehicles

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Abstract. *A wideband I-type rectangular waveguide rotary joint (RJ) is designed, simulated and built. It has an excellent performance over the whole Ku Band (10.7-14.5 GHz) where the return loss is less than -23 dB at its highest and the insertion loss is below 0.4 dB. The rotary joint is specifically designed for satellite news gathering (SNG) vehicles providing elevation and azimuthal movement to the antenna and matching polarization when it is needed at the feed. It can also be used in other high power microwave applications, where rotation ability of the antenna is a must during the transmission such as radars.*

Keywords

Ku-band, rotary joint, ridge waveguide, SNG vehicle, quarter-wave transformer,

1. Introduction

Traditionally there are two solutions for guided electromagnetic wave transmission in microwave communication. One solution is to carry the RF signal through coaxial cable and the other one is to guide the wave using waveguides. For the applications where high power transmission and low loss are needed, waveguides provide the best solution. High power signals are guided by commercial WR-75 waveguides in a Ku-Band front-end system where WR-75 is a waveguide flange standard that is defined by Electronic Industries Alliance (EIA). Rigid waveguides have been widely used in satellite communication applications, however most of the antenna systems in these applications require full rotation ability without causing any performance degradation and rigid waveguides restrict the movement of the antenna system. Providing the ability of rotation in either elevation or azimuthal direction, a bearing system must be implemented between two waveguide structures. Additionally ensuring circular rotation, a rectangular to coaxial waveguide transition is needed and the device that ensures such mobility is known as rotary joint in the literature. A rotary joint is basically a transition from rectangular waveguide to a coaxial or circular waveguide and then to another rectangular waveguide as longitudinal cross section can be seen in Fig. 1. Inevitably mismatches occur at both junctions, however most of the rotary joints are required to turn 360° around, providing low loss without any interruption during the transmission. Ku-band rotary joints become significant especially in SNG vehicles where usually three different Rotary joints are needed in each system. Two of them are used to change azimuth and elevation angles and another one is used for polarization correction. Although some applications use flexible waveguides for polarization correction, this causes unusual loss in the system especially after normal wear and tear. The joints for elevation and azimuth control must perform over the transmit frequency band of 13.75 to 14.5 GHz. The one for polarization correction should cover the whole Ku-Band. Commonly, Ku band Rotary joints are designed for transmit band, 13.75 to 14.5 GHz noting that 10.7 to 12.75 GHz is the receive band for Ku band applications. In this work, the rotary joing covers the whole Ku-Band and mechanically constructed in such a way that it could be used as a joint for all three purposes.

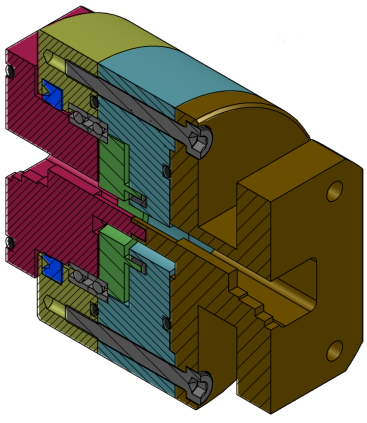


Fig. 1. 3D CAD drawing of the rotary joint

1.1 Literature Review

Design and development of rotary joints have been reported in [1-16]. A single channel RJ presented in [1] consists of two septum polarizers. This RJ is designed to

provide return loss of -15 dB, insertion loss of max. -0.8 dB and the isolation less than -17 dB in the frequency range 35-41 GHz. A compact, 2.3 λ_g, single channel RJ operating at 35.0 GHz is presented in [2]. It consists of two identical TE_{01} mode converters, clasping each other by a bearing. The RJ handled up to a peak input power of 210 W with a duty cycle of 18%. In [3], a U-style single channel waveguide RJ containing a rectangular waveguide TE_{10} mode to circular waveguide TM_{01} mode converter is described where return loss is less than -35 dB over the 6% of the Ka-band and return loss is less than -25 dB over 10% of the Ka-band. In [4], it is shown that incorporating ridge-waveguide sections, a single-channel waveguide RJ can be designed, which simultaneously provides high power handling capability up to peak power of 250 kW. In [5], full wave analysis of non-contacting RJ choke design is elaborated. Analysis is summarized for the possibilities including linearly polarized TM_{01} and/or TE_{01} modes in circular waveguide, circulary polarized TE_{11} modes in circular waveguide, or TEM modes in coaxial waveguide. A simple experimental procedure to match and to tune the 'door-knob' type microwave coupler that excites TM_{01} mode in circular waveguide from a rectangular waveguide has been presented in [6]. Some Rotary joints designed to transmit multiple channels. References in [7], [8] and [12-15] report on such rotary joints. Coaxial to ridged waveguide transition is used for the broad-band rotary joint in [9] and the VSWR is less than 1.7 between 0.85 GHz to 2.7 GHz. A high-power single channel waveguide RJ is described in [10], where 1:16 waveguide power divider is used to generate TE_{01} mode in the circular waveguide. A four step binomial impedance transformer is used to convert from the one-half E dimension output of the splitters to the full E input of the next two splitters. These transformers were tested at a power of 1.4 MW across 10% bandwidth without reaching breakdown with a maximum VSWR of 1.15. Tomiyasu, [11], built an annular rotating joint that permits multiple stacking to provide a number of channels with the help of directional couplers and E-plane joints. A dual channel RJ based on the excitation of circularly symmetric TM_{01} and TE_{01} modes in a circular waveguide is described in [12]. The RJ reported in [13], has insertion loss between 0.7 and 1.6 dB over the 26-40 GHz band and S_{22} is below -10 dB over the 26-40 GHz band, except 34.5 GHz, where it punctually reaches -8 dB. In [14], a general design method for N-channel RJ is introduced. They have designed a six channel RJ by using transition between concentric coaxial lines and double-ridged waveguides. Detailed choke design for coaxial waveguides are presented in [15],[16]. In [16] Ka band rotary joint is designed with additional physical capability which can carry 2 kg antenna but the band width is only 1.5 Ghz.

2. Design Procedure

In this section, design goals and theoretical justification of the rotary joint will be given.

2.1 Design Parameters

Although choke design is essential for rotary joints, in this design physical short is preferred since choke works ideally just for one frequency. Detailed choke design for coaxial waveguides is presented in [15]. At the beginning it was assumed that at the coaxial waveguide junction, wall currents pass through without any performance degradation due to the fact that normal components of the current density vector is continuous across the junction so that EM field will not be disturbed.

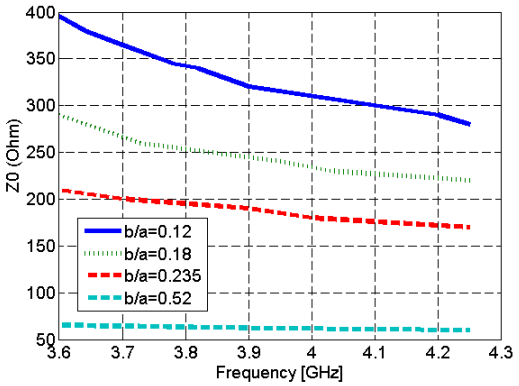


Fig. 2. Characteristic impedance of the TE_{11} mode in coaxial waveguide

The bearing system of the RJ is assumed as a continuous coaxial waveguide. All materials are assumed as PEC. Other noteworthy aspects of the rotary joint design include:

- Rotary joint's expected power capacity. Inner and outer radii of coaxial waveguide are related to that power.
- Impedance matching network design to match rectangular waveguide to coaxial waveguide using ridged waveguides.

Keeping the aforementioned points in mind, the design goals are given below for the rotary joint.

- Operating Frequency: 10.7 GHz - 14.5 GHz
- First Port: WR-75 Rectangular Waveguide, a: 19.05 mm, b: 9.525 mm (a: 0.75 in, b: 0.375 in)
- Second Port: WR-75 Rectangular Waveguide a: 19.05 mm, b: 9.525 mm (a: 0.75 i, b: 0.375 in)
- Return Loss: <-23 dB
- Insertion Loss: <0.4 dB
- Power Handling Capacity: 1000W

2.2 Theoretical Background

In the dominant TE_{10} mode, wave impedance of WR-75 waveguide is given by

$$Z_\omega = \frac{n_0}{\sqrt{1-(\frac{f_c}{f})^2)}} \tag{1}$$

It must be noted that impedance of a rigid waveguide is frequency dependent. As shown in Fig. 2 the wave impedance of coaxial waveguide is also frequency dependent. The incident RF signal in WR-75 side is dominant TE_{10} mode. As mentioned before, coaxial waveguide is used in the rotating section where the dominant TE_{10} mode is converted to the circular TE_{11} mode.

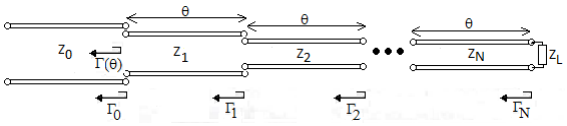


Fig. 3. Multiple quarter-wave transformer structure

Our aim is to carry the incident signal through RJ ensuring the rotation with reasonably low reflection and insertion loss, which are as known as S_{11} and S_{12} respectively in the nomenclature. This is a well-known wide band impedance matching problem between the rectangular waveguide and coaxial waveguide junction, noting that rotary joint is a reciprocal device. Wave impedances of both waveguides are frequency dependent as it can be inferred from (1) and Fig. 2, however, referring to Fig. 2 again, the wave impedance of the coaxial waveguide approaches to a constant where the inner (a) and the outer (b) radius is 0.52 for the given frequency band. Although Fig. 2 does not include our target frequency band, it is clear that when b/a ratio approaches to 0.5,the impedance of the waveguide does not change with frequency and it converges to 50Ω . Due to the fact that, b/a ratio of the rotary joint is chosen to be 0.52 to achieve a broadband design. Impedance matching between rectangular and coaxial waveguide, is provided by N-1 quarter wave transformers as shown in Fig. 3. The length θ_N of each section must be an odd factor of quarter wavelength and impedance Z_n of each section must be found. Z_N is taken approximately 50Ω which represents the coaxial waveguide's impedance that will be chosen for b/a=0.5 as in Fig. 2, and Z_0 represents WR-75 waveguide's impedance.

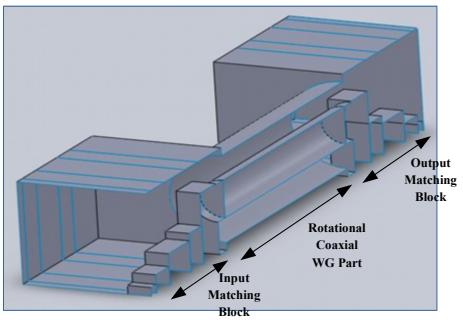


Fig. 4. WR-75 to coaxial waveguide transition - longitudinal cross section

At the beginning of the simulation process this impedance (Z_0) value is calculated at the middle of the Ku Band (12.42 GHz). N-1 waveguide sections are realized by using ridge waveguide as shown in Fig. 4 which is also known as ladder transition. The height of the ladders (ridges) will provide requested impedances [9]. According to the theory of small reflections [17], the input reflection coefficient is defined as;

$$\Gamma(\theta) = A\sum_{n=0}^{N} C_n^N e^{-2jn\theta} \tag{2}$$

$$\Gamma(\theta) \approx \Gamma_0 + \Gamma_1 e^{-2j\theta} + \Gamma_2 e^{-4j\theta} + \ldots + \Gamma_N e^{-2jN\theta}. \tag{3}$$

where

$$\Gamma_n = \frac{Z_{n+1} - Z_n}{Z_{n+1} + Z_n}\,,\ \Gamma_N = \frac{(Z_L - Z_N)}{Z_L + Z_N} \tag{4}$$

These results are useful when all Z_n increase or decrease monotonically across the transformer and Z_L is real which implies that Ω_n will be real with the same sign. Reflection coefficient of the adjacent junctions is small and increasing the number of transmission line section helps to reduce input reflection coefficient. This theory is known as the theory of small reflections and it is described briefly in equations (3) and (4). The input reflection coefficient of this transformer is given in (3). If the reflection coefficients at the junctions are selected as a function of Chebyshev polynomial coefficient, the transformer is called as Chebyshev transformer [17]. These reflection coefficients can also be selected as a function of binomial polynomials where such a transformer is called as binomial transformer which is also known as maximally flat transformer. Once the reflection coefficient is selected then impedance of the quarter wave sections could be calculated using (4).

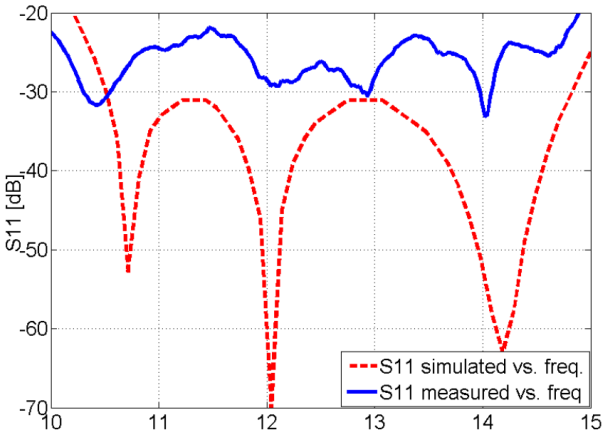


Fig. 5. Simulated and measured return loss results versus frequency

In the initial design, Γ_0 to Γ_N coefficients were selected as a function of Chebyshev polynomial coefficients. Chebyshev transformer's impedance values Z_1 to Z_{N-1} are calculated from (4).Impedance of a rectangular double ridge waveguide is given by [18];

$$Z = \frac{\pi n_0}{sin\theta_2 + (\frac{d}{b})[\frac{B}{Y_{01}} + tan\frac{\theta_1}{2}]cos\theta_2}(\frac{b}{a})(\frac{d}{b})(\frac{a}{\lambda_c}) \tag{5}$$

$$\theta_1 = \pi(1 - \frac{s}{a})(\frac{a}{\lambda_c}), \theta_2 = \pi(\frac{s}{a})(\frac{a}{\lambda_c}) \tag{6}$$

where B/Y_{01} stands in for step discontinuity on sides of the ridge and could be approximated as follows from [19];

$$\frac{B}{Y_{01}} \approx 4\left(\frac{b}{a}\right)\left(\frac{a}{\lambda_c}\right)\ln\operatorname{cosec}\left(\frac{\pi d}{2b}\right) \tag{7}$$

More details on ridge waveguides can be found in [20].

As a starting point for the optimization, the aforementioned parameters are used as initial values. Simulation and optimization of the rotary joint is realized by WASP-NET EM simulation software. In addition to avoid electrical breakdown at high power levels, appropriate shortest distance is taken into account.

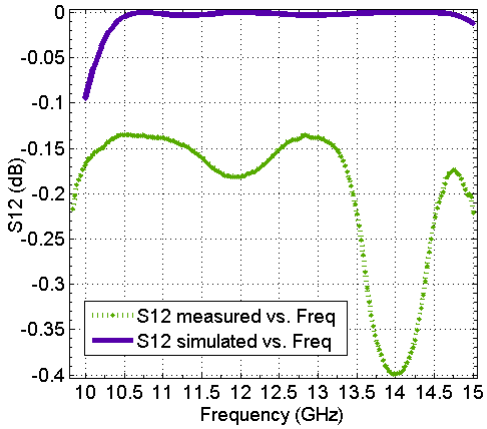


Fig. 6. Simulated and measured insertion loss results versus frequency

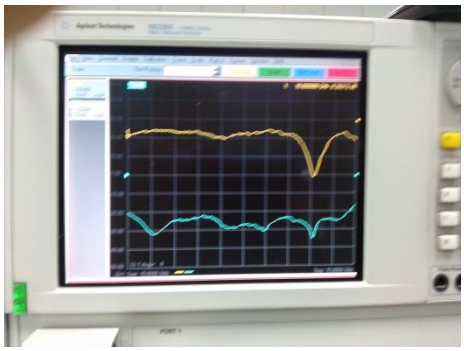


Fig. 7. Measured insertion loss and return loss of the fabricated rotary joint

3. Simulation and Test Results

Fig. 5 and Fig. 6 show the measured and simulated results for return loss and insertion loss respectively. Over the whole band (10.7 GHz - 14.5 GHz) return loss is below -23 dB and insertion loss is below 0.4 dB. In Fig. 6, it can be easily deduced that insertion loss is less than 0.2 dB which means 95% of input power passes through rotary joint without any loss for 80% of the whole KU band. Between 13.5-14.5 GHz insertion loss exceeds 0.2 dB and reaches its maximum punctually at 14 GHz which is 0.4 dB that means 90% of input power passes RJ without any loss. These results are in line with the design goal given in section 2.1. A technical drawing for the bearing system is given in Fig. 1. RF test setup for the manufactured rotary joint is shown in Fig. 8.

4. Conclusion

A wide band (over 30%) rotary joint that covers the whole Ku band is designed, simulated, built and tested. The rotary joint could be used for polarization correction, elevational and azimuthal direction purposes in a satellite news gathering (SNG) vehicle. The initial impedance matching design was based on the theory of small reflections. The CAD software, WASP-NET, was then used to optimize the dimensions. As shown in Fig.5 and Fig.6, the simulation results exceeded the design goals. 6061 aluminum alloy was used for producing the prototype and no other optimization, such as silver coating, was applied to the rotary joint. Although a tolerance analysis was carried out before the manufacturing process, the measured results showed some differences with the simulated ones. These differences may be due to the assumption of perfect electric conducting (PEC) material in simulation, imperfections occured in the milling process and the bearing discontinuites in the rotating section of the rotary joint

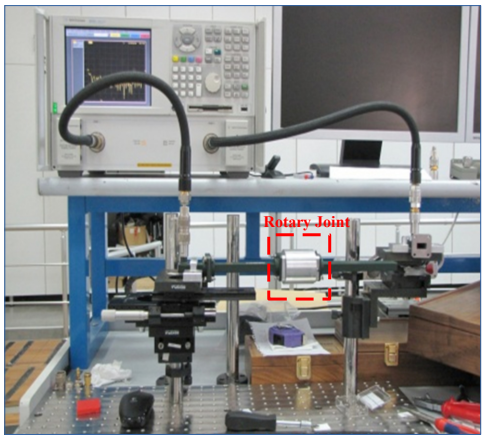


Fig. 8. Measurement setup of the fabricated rotary joint

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References

[1] KAIDEN, M., KIMURA, K., OGAWA, H., et al. Septum polarizer for Ka-band H-shaped rotary joint. *J. Infrared Millimeter Terahertz Waves*, 2009;Vol. 30, p. 727-737. DOI: 10.1007/s10762-009-9491-9

[2] CHANG, TH., YU, BR., High-power millimeter-wave rotary joint for radar applications. *Review of Scientific Instruments*, 2009, 80: 034701-034704. DOI: 10.1109/ICIMW.2009.5325680

[3] ABRAMOV, VI., PARK, HJ., KIM, DH., LEE, TH. U-style rotary joint with E_01 mode for millimeter waves. *Microwave Symposium Digest, 2004 IEEE MTT-S International*. Fort Worth (USA),June 2004, p. 1879-1882. DOI:10.1109/MWSYM.2004.1338974

[4] Rambabu K, Bornemann J. Compact single channel rotary joint using ridged waveguide sections for phase adjustment. *Microwave Theory and Techniques, IEEE Transactions on*, 2003, vol. 51, p. 1982-1985. DOI: 10.1109/TMTT.2003.815269

[5] McNamara DA, Hildbrand LT. Fullwave analysis of noncontacting rotary joint choke sections using the generalized scattering matrix (GSM) approach. *IEE Proceedings-Microwaves, Antennas and Propagation*, 2003, vol. 150, p. 5-9. DOI: 10.1049/ip-map:20030438

[6] Franco MAR, Serrao VA, Fuhrmann C, Herdade SB. A simple procedure for impedance matching and tuning of microwave couplers for an electron linear accelerator. *Microwave Theory and Techniques, IEEE Transactions on*, 2001, vol. 49 p. 562-564. DOI: 10.1109/22.910565

[7] Woodward OM. A dual-channel rotary joint for high average power operation. *Microwave Theory and Techniques, IEEE Transactions on*, 1971, vol. 18, p. 1072-1077. DOI: 10.1109/TMTT.1970.1127413

[8] Boronski S. A multichannel waveguide rotating joint. *Microwave*, 1965, vol. 8 p. 102-105.

[9] Muenzer PJ. Broadbanding coaxial-to-ridged-wave-guide transitions. *Microwaves*, 1964, vol. 3, p. 92-96.

[10] Smith PH, Mongold GH. A high-power rotary waveguide joint. *Microwave Theory and Techniques, IEEE Transactions on*, 1964, vol. 12, p. 55-58. DOI:10.1109/TMTT.1964.1125751

[11] Tomiyasu K. A new annular waveguide rotary joint. *Proceedings of the IRE*, 1956, vol. 44, p. 548. DOI: 10.1109/JRPROC.1956.274939

[12] Raabe HP. A rotary joint for two microwave transmission channels of the same frequency band. *Microwave Theory and Techniques, IRE Transactions on*, 1955, vol 3., no: 4, p. 30-41 . 10.1109/TP-GAP.1952.237413

[13] Zürcher ZF. A 6.5-50 GHz battery-powered compact rotary joint for polarization elipticity measurement.*Microwave and Optical Technology Letters*, 2011,vol. 53, no: 2, p. 375-379. DOI:10.1002/mop.25692

[14] Mallahzadeh A., Ahmadabadi H. Design of N-Channel rotary joint using curved double ridged waveguide and concentric coaxial lines. *ACES Journal-Applied Computational Electromagnetics Society*, 2012, vol. 27:1, p. 50.

[15] King HE. Broad-band coaxial choke coupling design. *Microwave Theory and Techniques, IRE Transactions on*, 1960, vol. 8, p. 132-135. DOI: 10.1109/TMTT.1960.1124711

[16] Yevdokymov A., Kryzhanovskiy V., Pazynin V., et al. Ka-band waveguide rotary joint,*Microwaves, Antennas & Propagation, IET*, 2013, Vol. 7, no. 5, p. 365-369 DOI:10.1049/iet-map.2012.0326

[17] Pozar DM, Microwave Engineering, 3rd ed. NY, USA: John Wiley & Sons Inc, 2010.

[18] Hoefer, W.J.R., Burton, M.N., Analytical Expressions for the Parameters of Finned and Ridged Waveguides. *Microwave Symposium Digest, 1982 IEEE MTT-S International*, 1982, p.311-313. DOI: 10.1109/MWSYM.1982.1130702

[19] Marcuvitz N. Waveguide handbook. *Boston Technical Publishers edition*, 1964.

[20] Helszajn J. Ridge waveguides and passive microwave components. *IET*, 2000, ISBN: 978-0852967942.

[21] Uher J., Bornemann J., Rosenberg U. Waveguide Components for Antenna Feed Systems: Theory And CAD, *Artech House*, 1993, ISBN: 978-0890065822.

[22] Bostan SM. KU Band Waveguide Component Design for SNG Vehicles. MSc Thesis, *Yıldız Technical University*, 2011 Istanbul, Turkey.

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