Design of N-Channel Rotary Joint using Curved Double-Ridged Waveguide and Concentric Coaxial Lines

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***Abstract* ─** In this paper, a general design method for a special kind of N-channel rotary joint is presented. The N-channel configuration is achieved by using transition between concentric coaxial lines and double-ridged waveguides. Design of double-ridged waveguides for the purposed transition is also presented. Based on this method, an ultra wide band six-channel rotary joint is designed for a frequency band of 8 to 18 GHz. A full-wave numerical simulation tool is used to optimize the geometry of the proposed six-channel rotary joint to achieve a compact size, wide bandwidth operation, and low insertion loss. Simulated results show the insertion loss of less than 0.5 dB and VSWR ≤ 2 for all channels over the entire frequency bandwidth. Finally, the sensitivity analysis is done to obtain the effect of the manufacturing tolerances on performances of the rotary joint.

***Index Terms* ─** Concentric coaxial lines, double-ridged waveguide, rotary joint.

I. INTRODUCTION

The rotary joint is an integral part of rotational microwave communication systems, such as spacecrafts [1] and tracking radar systems [2]. It is an electromechanical device that provides a critical interface between the stationary and rotating section of system, allowing signals to be transmitted back and forth between the antenna and pedestal with little distortion and low insertion loss. Although different types of rotary joints are used extensively in commercial and military applications but they have not been reported in the open literature.

In radars or seeker antennas, it is often necessary to have a multi-channel rotary joint to transmit two or more RF signals through a rotational axis. The operation frequencies of channels are dependent on their applications so channels can operate at the same or different frequencies. The connection of multi-channel rotary joint to the antenna, i.e., movable part of system, and the stationary part of system is through transmission lines which support circularly symmetric propagating modes. These types of modes are needed to avoid distortion of signal when it is transmitted along the axis of rotation, due to rotation of device around the axis. The transmission lines which support the propagation of circularly symmetric modes are circularly waveguides excited in the TM_{01}, TE_{01}, or circularly polarized modes and coaxial lines which propagate TEM mode. These propagating modes have radial electromagnetic fields distribution and fields are only the function of radius, so their propagation is not affected by rotation of rotary joint and the phase shift is small due to rotation. Rotary joints which use circular waveguide with the TM_{01} or TE_{01} modes have low insertion loss and high power handling capability. The operational bandwidths of these types of rotary joints are limited by the bandwidth of the transducers which are used for excitation of these modes [3] and are also limited by the generation of higher order modes. The rotary joints that use the circular waveguide with circularly polarized mode have wider bandwidth compared to TE_{01} or TM_{01} modes [4]. The disadvantage of mentioned rotary joints is the difficulty in design of multi-channel configurations. The TEM coaxial line has wider single mode operation compared to cylindrical

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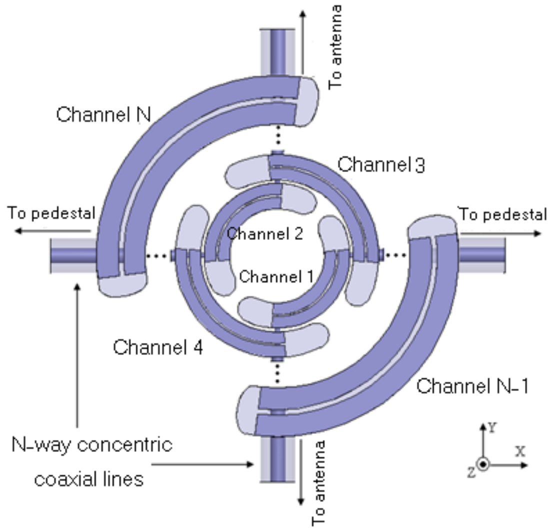
waveguide and multi-channel rotary joint can be designed by using concentric coaxial lines configuration [1, 5]. But the rotary joints which use the coaxial transmission line contain transition of coaxial line to rectangular waveguide that often prevent the rotary joint from being a wideband structure [5]. Forward-mounted antennas in the missile function in the role of seeker of target. If the seeker antenna beams steers mechanically, a rotary joint is needed to transmit the received signals by the antenna to stationary part of system. These signals are utilized to guide the missile to the target. In this paper wideband characteristics and N-channel configuration of the seeker antenna rotary joint are achieved through utilizing of double-ridged waveguides together with concentric coaxial transmission lines. Double-ridged waveguides have preferential features for using in broadband applications such as low cutoff frequency and wide bandwidth. Ridged waveguides satisfy requirements of applications that need to have a transmission line with a single mode of propagation over extensive bandwidth. For a given frequency bandwidth, ridged waveguides have smaller cross section compared to conventional rectangular waveguides. An additional advantage follows from the fact that the ridged waveguides have low and flat characteristic impedance compatible with the coaxial line. The above mentioned features of ridged waveguides make them suitable candidates for using in rotary joint. In the following, the configuration of N-channel rotary joint is described and then designs of different part of it are presented in detail.

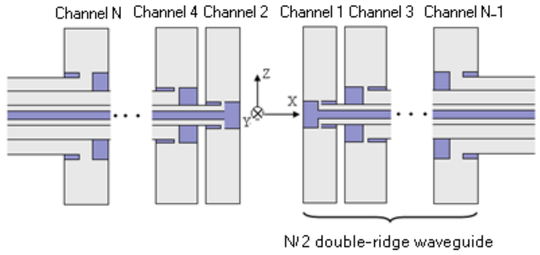
II. DESIGN CONSIDERATIONS

A. N-channel rotary joint configuration

Figure 1 shows configuration of the designed rotary joint. This configuration consists of N double-ridged waveguides. Each of the waveguides is considered as a channel to transfer signals between the two coaxial lines which are at right angles and are connected to the antenna and pedestal. Coaxial lines, which their axes are aligned with x axis, are considered for connecting to the stationary part of the system or pedestal and coaxial lines with axes aligned with y axis are connected to antenna. Due to need of rotation around the unique axis, use of coaxial line with separate axes is impossible therefore concentric coaxial lines are used. Because of the right angle between input and output port of each channel, double-ridged waveguide must have curved form to make the connection between two coaxial lines possible. Curved forms of waveguides provide the advantage of having a compact structure since they can be arranged circularly around a center in a cylindrical volume. In this configuration t,he number of channels is even and they are completely isolated. The operating frequency of each channel depends on dimensions of its waveguide and coaxial line. As depicted in Fig. 1(b), N-channel rotary joint consists of transitions from N/2 coaxial lines with concentric configuration to N/2 double-ridged waveguides placed next to each other, with different dimensions that must be designed.



(a)



(b)

Fig. 1. Configuration of N-channel rotary joint. (a) Top view. (b) Cutaway in XZ plane.

B. Design of double-ridged waveguides

In Fig. 2, the transition between N concentric coaxial lines to N double-ridged waveguides placed next to each other is shown. Concentric coaxial lines contain N+1 conductors comprising N coaxial transmission lines. Diameters of outer and inner conductors of the nth coaxial line are denoted by D_{n+1} and D_n, respectively, so the characteristic impedance of the nth line is given by:

$$Z_n = \frac{60}{\sqrt{\varepsilon_r}} \ln \frac{D_{n+1}}{D_n}, \tag{1}$$

where ε_r is the relative permittivity of insulator filled between lines. The signal of nth coaxial line is coupled to nth double-ridged waveguide. To have a well-matched transition between the coaxial line with predetermined arbitrary line impedance and the double-ridged waveguide, following design considerations must be taken into account:

1- The characteristic impedance of double-ridged waveguide must be as close as possible to the predetermined impedance of coaxial line.
2- The size of outer diameter of the nth coaxial line should be close to the ridge width of nth waveguide.
3- The cutoff frequency of TE_{10} mode of double-ridged waveguide must be excited before than the low end of the desired band, and cutoff frequencies of higher TE_{m0} modes, especially odd modes, must be larger than the high end of band.
4- The higher non-TEM modes of coaxial line must be cutoff in desired bandwidth. The second propagating mode in the coaxial line is the TE_{11} mode. The cutoff frequency of the TE_{11} mode of nth coaxial line is approximately given by[6]:

$$f_c = \frac{c}{\pi\sqrt{\varepsilon_r}\,(D_{n+1}+D_n)}, \tag{2}$$

where c is the speed of light in the free space.

Taking into account of above considerations also avoids propagation of higher order modes in all channels. Some undesired modes can be excited in the vicinity of junction but they are evanescent.

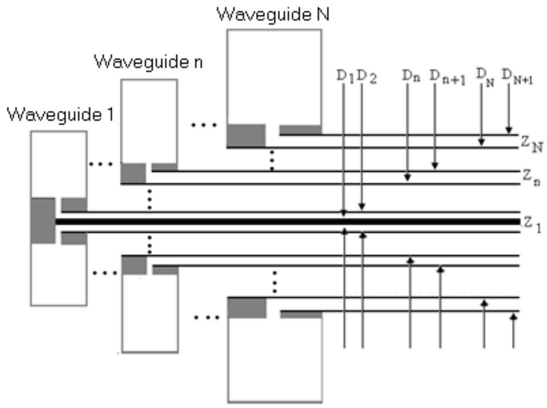


Fig. 2. Transition of N concentric coaxial lines to N double-ridged waveguides.

For the purposed transition, the cutoff frequencies of first propagating mode and higher order modes need to be determined for designing of each double-ridged waveguide. Hopfer [7] presented curves to determine cutoff frequencies for specified aspect ratio but they are not applicable to this design since to meet the characteristic impedance criterion different aspect ratios are needed. Pyle [8] extended the work of Hoefer and presented the design data for ridged waveguides of any aspect ratio but without considering characteristic impedances of waveguides. In 1982, closed form expressions, for calculating the cutoff frequency of TE_{10} mode and the characteristic impedance of double-ridged waveguide were obtained by perturbation theory [9]. The cutoff frequency of the double-ridged waveguide, with cross section as depicted in Fig. 3, is given by the following formula

$$f_c = \frac{1}{2(a-s)\sqrt{\varepsilon_r \mu_r}}[1+\frac{4}{\pi}\left(1+0.2\sqrt{\frac{b}{a-s}}\right)\frac{b}{a-s}. \\ \ln\csc\frac{\pi}{2}\frac{d}{b}+(2.45+0.2\frac{s}{a})\frac{sb}{d\left(a-s\right)}]^{-\frac{1}{2}}, \tag{3}$$

where a and b are the waveguide width and height, respectively, s is the ridges width and d is the spacing of two ridges. This formula has 1 percent accuracy in determining the cutoff frequency with parameters in the following ranges:

$$0.01 \le \frac{d}{b} \le 1$$

$$0 < \frac{b}{a} \le 1$$

$$0 \le \frac{s}{a} \le 0.45$$

And the characteristic impedance obtained by voltage-power approach is

$$Z_0 = Z_{0\infty}\left[1-\left(\frac{f_c}{f}\right)^2\right]^{-\frac{1}{2}}, \qquad (4)$$

where

$$Z_{0\infty} = \frac{120\pi^2 (\frac{b}{\lambda_c})}{\frac{b}{d}\sin\pi\frac{s}{b}\frac{b}{\lambda_c} + [\frac{B_0}{Y_0} + \tan\frac{\pi}{2}\frac{b}{\lambda_c}(\frac{a-s}{b})]\cos\pi\frac{s}{b}\frac{b}{\lambda_c}}. \quad (5)$$

$Z_{0\infty}$ is the characteristic impedance when frequency approaches infinity and λ_c is related to cutoff frequency by $\lambda_c = c / f_c$. The use of (3) and (4) is easy so are chosen for designing of the waveguides.

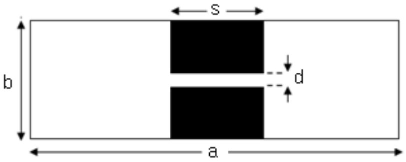


Fig. 3. Cross section of double-ridged waveguide.

Cutoff frequencies of higher order modes can be determined by applying the transverse resonance method. The following transcendental equations are obtained for TE_{m0} cutoff frequencies [7]. For m odd

$$\cot\frac{\pi(a-s)}{\lambda_c} - \frac{b}{d}\tan\frac{\pi s}{\lambda_c} - \frac{B}{y_0} = 0. \qquad (6)$$

And for m even

$$\cot\frac{\pi(a-s)}{\lambda_c} + \frac{b}{d}\cot\frac{\pi s}{\lambda_c} - \frac{B}{y_0} = 0. \qquad (7)$$

The (6) and (7) must be solved for λ_c to determine the cutoff wavelengths or frequencies of TE_{30} and TE_{20}, respectively. In the above equations, the term B/y_0 is the normalized discontinuity susceptance of ridges obtained by Marcuvitz [10]. The cutoff frequency of TE_{20} is slightly varied by changing the dimensions of the ridges. Its value depends mainly on the value of the waveguide width, so the choice of the cutoff frequency of TE_{20} mode upper than the high end of the bandwidth, approximately determines the size of waveguide width [11]. The dimension of ridge width can be adjusted by considering the cutoff frequency of the TE_{30} mode and the attenuation of waveguide. After selecting the waveguide and ridge width, the (3) and (4) must be solved for various values of b and d to obtain dimensions which satisfy the required cutoff frequency and characteristic impedance of the first propagating mode. Finally, for the determined values of waveguide dimensions, the (6) and (7) must be solved for f_c to ensure that the cutoff frequencies of higher order modes are larger than the high end of the frequency band.

C. Design of rotary joint channels

The structure of one channel of the rotary joint is depicted in Fig. 4. It consists of two coax to double-ridged waveguide transformers and a uniformly curved form of double-ridged waveguide. In the design of the purposed rotary joint, it is important to keep the overall configuration compact; therefore, the radius of the curvature of the waveguide should be chosen as little as possible. The radius of the curvature of the waveguide must also be chosen such that the VSWR contribution due to the curved form of the waveguide becomes negligible in the whole bandwidth. In the transition of the coax to the curved double-ridged waveguide, three parameters are important to achieve good VSWR. They are the shape and the length of the cavity and the lengths of the two ridges which means where these two ridges stop in the cavity [12, 13].In this design the cavity of transformer has the same curvature of waveguide to reduce the reflection between the waveguide and transformer. To improve the VSWR, the junctions of the outer and inner conductors of the coaxial line must be as close as possible to the end of ridges inside the transformer; it means that the ridges must stop close to the junction inside the cavity. Finally, the end of the cavity has to be shorted by properly shape plate which results in the best VSWR.

III. DESIGN OF SIX-CHANNEL ROTARY JOINT

In this section based on suggested design method, a six-channel rotary joint has been designed and simulated for the frequency bandwidth of 8 to 18

GHz. This frequency bandwidth covers both X and Ku band. These bands are commonly used in the Seeker missile. Figure 5 shows the configuration of the six-channel rotary joint. It has the same configuration of the N-channel prototype, but is placed inside an aluminum body. Due to the symmetry of the rotary joint, the configurations of channels 1, 2, and 3 are exactly the same as channels 4, 5, and 6, respectively, so in the following just designs and simulations of channels 1 to 3 are presented. As depicted in Fig. 5(b), there is a transition between three concentric coaxial lines and three double-ridged waveguides, so three double-ridged waveguides have to be designed for the frequency bandwidth of 8 to 18 GHz with the assumption that line impedances of all concentric coaxial lines are 50 Ω. This transition is shown separately in Fig. 6. It follows from the (1) that the relationship between the diameters of three 50 Ω air filled coaxial lines with concentric configuration, as depicted in Fig. 6, is

$$D_3 = 2.3 \times D_2 = 2.3 \times 2.3 \times D_1. \qquad (8)$$

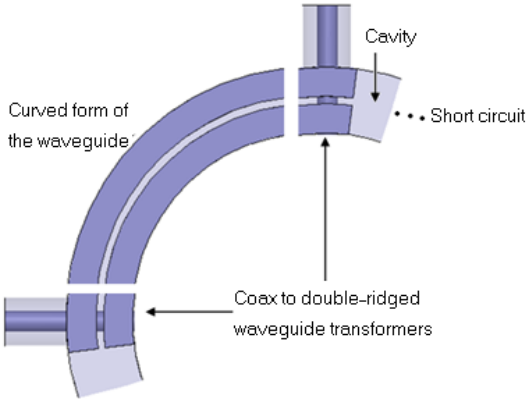
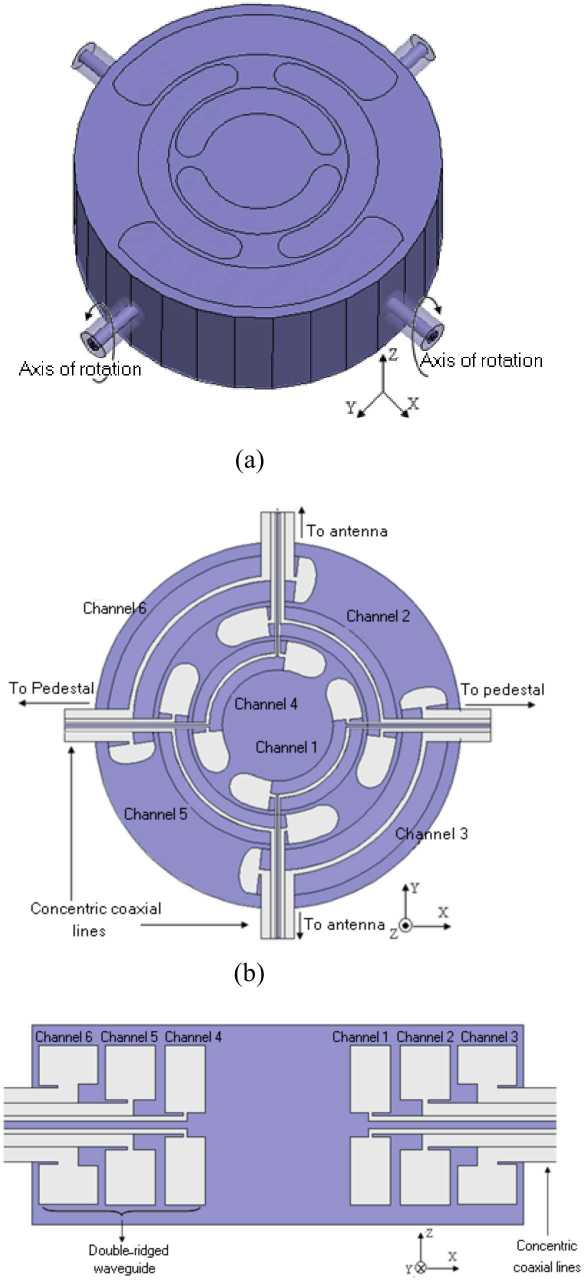


Fig. 4. Structure of one channel of rotary joint.

As mentioned above, choosing the ridge width of waveguide close to the outer diameter of the coaxial line provides better transition so the ridges widths of three waveguides must be close to D_1, D_2, and D_3, so ratios between the ridges widths of adjacent waveguides must be about 2.3. This causes difficulties in the design of double-ridged waveguides, since three waveguides with different ridges widths and the same operating bandwidth are needed. In double-ridged waveguides, operating bandwidth is the frequency range in which there is just one propagating mode, but this bandwidth is not the useful bandwidth, so the cutoff frequency of the dominant mode is commonly chosen 15 to 25 percent lower than the low end of the desired bandwidth [7]. Assuming the operating bandwidth between 8 to 18 GHz, three waveguides with different dimensions must be designed by considering the following constraints:



(c)

Fig. 5. Configuration of six-channel rotary joint. (a) 3D view. (b) Cutaway view in XY plane. (c) Cutaway in XZ plane.

1- Cutoff frequencies of their dominant modes should be lower than 6 GHz (25% of the 8 GHz).
2- Higher propagating modes especially TE_{30} must be excited above the 18 GHz.
3- Characteristic impedances of waveguides must be around 50 Ω.
4- Ratios of ridges widths of adjacent waveguides must be approximately 2.3.

The design is based on the method mentioned previously. The cutoff frequency of the TE_{20} mode depends on the size of the waveguide width. Its size is chosen to be 16 mm for three waveguides. Larger width of the ridge leads to larger attenuation in the double-ridged waveguide [14] so width of ridge must be small as possible to keep the attenuation or insertion loss low.

As mentioned previously, the ridge width also is limited by the cutoff frequency of the TE30 mode which can be coupled to coaxial line. For these reasons the ridge width of waveguide 3 is chosen 1/4 of waveguide width, i.e. 4 mm. by considering (8), this size leads to 1.73mm and 0.75 mm for ridges widths of waveguides 2 and 3, respectively.

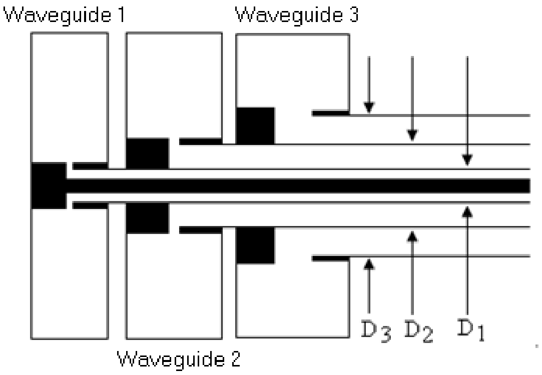


Fig. 6. Transition of three concentric coaxial lines to double ridged waveguide.

Since the power-handling capacity of rotary joint is not of concern, the aspect ratio of waveguides can be arbitrary. The double-ridged waveguide characteristic impedance increases with the spacing between ridges and inversely with the ridge width hence, ridges spacing must be decreased from waveguides 3 to 1. Finally for values of ridges spacing and waveguides heights which satisfy the previously mentioned requirement, nonlinear equations (4) and (5) have been solved by the least squares method [15]. Bandwidth specifications of the designed waveguides are presented in Table 1 and the characteristic impedances of them are depicted in Fig. 7. It can be seen that their values are in the range of 40 to 50 Ω in the entire bandwidth. Designed waveguides must be curved. The radiuses of curvatures of the waveguides of channels 1 to 3 have been optimized by HFSS [16]. The VSWR of the curved form of double-ridged waveguides are plotted in Fig. 8 which are lower than 1.06 across the whole bandwidth. Each curved waveguide is connected to two coax to waveguide transformers which their design method mentioned before. The end of the cavity has been shorted by various shapes of plates and the elliptical shape of the shorting plate resulted in the best results. The complete geometry of each channel can be described by means of angles of waveguide and ridge sectors, as shown in Fig. 9. The geometry of each channel has been modeled by HFSS and optimizations have been carried out for these parameters.

In Table 2, values of θ_i and radiuses of curvatures which result in desired properties of rotary joint are presented. Simulated insertion losses of channels are shown in Fig. 10(a). Their values are better than 0.3 dB for channels 1 and 2 in the frequency range 8 to 18 GHz and the insertion loss of channel 3 is less than 0.5 dB. The VSWR of all channels have acceptable values and are better than 2 over the frequency range of 8 to 18 GHz as depicted in Fig. 10(b).

Table 1: Cutoff frequencies of first three modes of designed waveguide in GHz

Modes	Waveguide A	Waveguide B	Waveguide C
TE_{10}	3.9	4.5	4.6
TE_{20}	23.2	20.7	19.6
TE_{30}	25.2	22.7	20.9

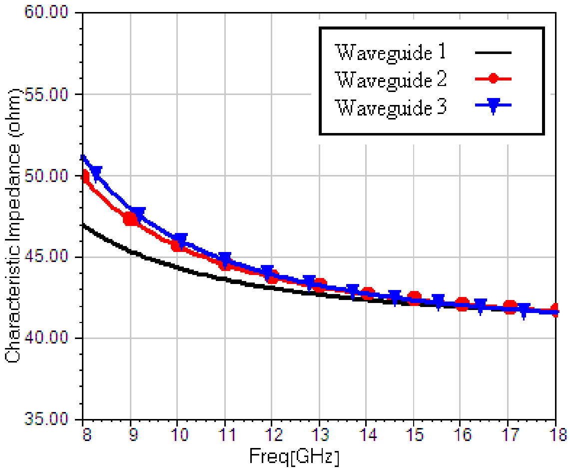


Fig. 7. Characteristic impedances of designed waveguides of channels 1 to 3.

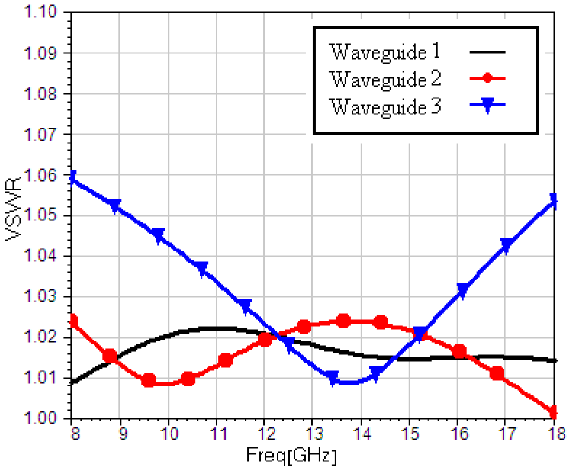


Fig. 8. VSWR of curved form of designed waveguides of channels 1 to 3.

The designed rotary joint must be connected to the stationary part through an appropriate choke types. The use of contacting choke is preferred for the non-contacting type for several reasons. The first reason is that the bandwidth of the contacting choke is greater than its non-contacting type. Although the broadband non-contacting choke can be designed for the coaxial line [17], the concentric configuration of coaxial lines of this rotary joint and its small dimensions makes design and fabrication of the non-contacting choke mechanically and electronically complex. The second reason relates to the rotation speed of the seeker antenna. Since the seeker antenna rotates gently, the contacting choke is suitable.

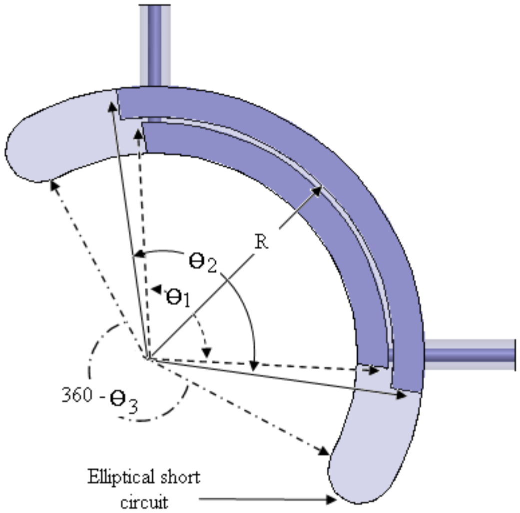


Fig. 9. Description of each channel by angles.

Table 2: Values of θ_i and R for three channels

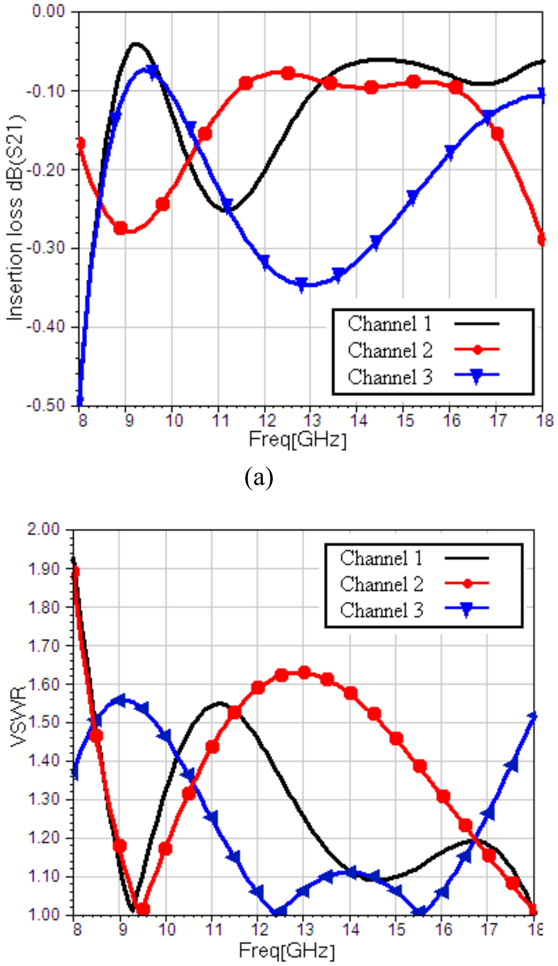
	Channel1	Channel2	Channel 3
Θ_1(deg)	103	96	94
Θ_2(deg)	105.3	98	95
Θ_3(deg)	111.7	138	125
R(mm)	17.3	12.25	8.8

IV. SENSITIVITY ANALYSIS

In this section, a comprehensive sensitivity analysis is carried out to obtain a clear insight of the effects of manufacturing tolerances on the performance of the proposed rotary joint, especially insertion loss. It reveals that the parts which are most sensitive to tolerances are diameters of coaxial lines. Figure 11 shows the effects of 0.05 mm tolerances of diameters of coaxial lines on the insertion loss for three channels. Tolerances of manufacturing often are less than 0.05mm. The results demonstrate that the most sensitive channel to tolerances is channel 1. It is obvious that the sensitivity increase as dimensions of channel is decreased.

V. CONCLUSIONS

A general design method for an N-channel rotary joint with a novel configuration has been suggested. In this design, double-ridged waveguides and concentric coaxial lines have been



(a)

(b)

Fig. 10. Simulation resluts of six-channel rotary joint. (a) Insertion loss. (b) VSWR.

utilized to achieve simultaneously multi-channel, compact configuration, complete isolation between channels, and wide band characteristics. A six-channel rotary joint has been designed by this method. The structure has been simulated using finite element package, HFSS. The results show the insertion loss of less than 0.5 dB and VSWR of less than 2 for six channels. Finally, the sensitivity analyses have been done to obtain effects of manufacturing tolerances on the characteristics of six-channel rotary joint.

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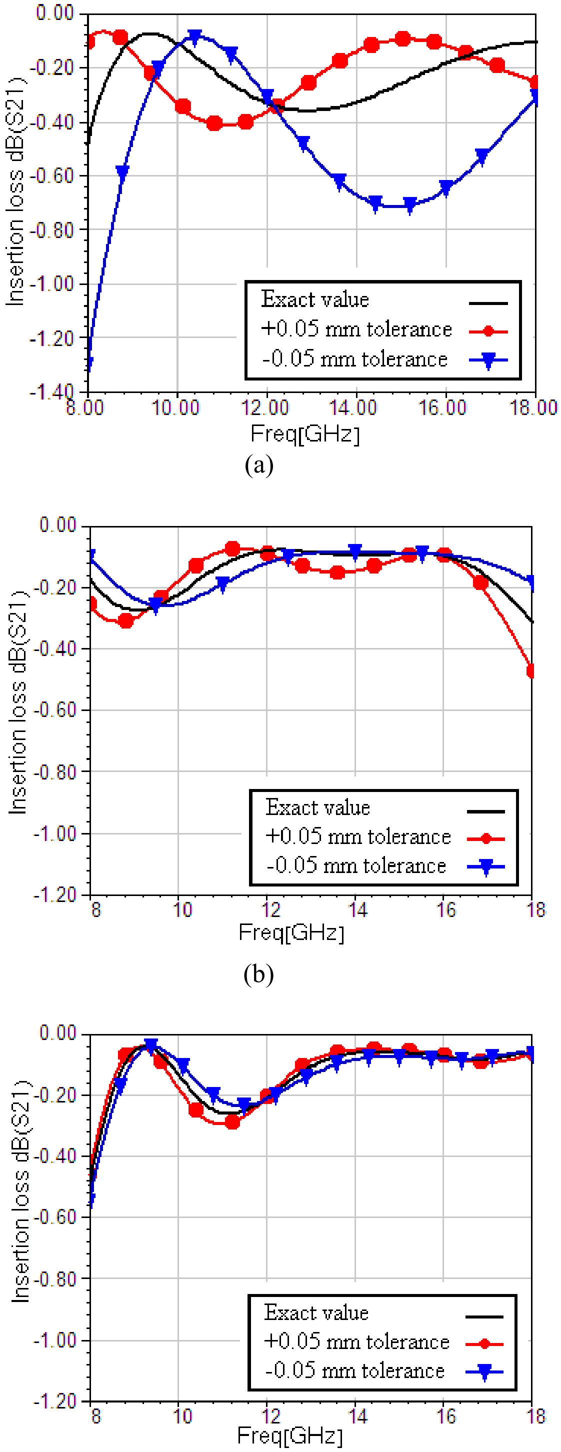

(a)

(b)

(c)

Fig. 11. Variations of insertion loss of channels by considerig tolerances of diameters of coaxial lines. (a) Channel 1. (b) Channel 2. (c) Channel 3.

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