Compact Single-Channel Rotary Joint Using Ridged Waveguide Sections for Phase Adjustment

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***Abstract*—A new design for single-channel waveguide rotary joints for high-power applications is presented. In order to obtain correct signal phase conditions along the ring and, at the same time, reduce the diameter of the rotary joint, tapered ridged waveguide sections are introduced. Design guidelines with respect to general transmission characteristics, H-plane aperture couplers, and ridge waveguide analysis are presented. Measurements of a 9.05-GHz prototype show less than 1-dB insertion loss over a 250-MHz bandwidth and, hence, verify the design concept.**

***Index Terms*—Dynamic couplers, ridge waveguides, rotary joints, waveguide couplers.**

I. Introduction

In TRACKING radar applications, rotary joints form the link between the stationary and movable parts of the microwave communication system. Their essential characteristics are high-power carrying capability, low insertion loss, and good impedance matching. Although a large variety of rotary joints involving coaxial or waveguide technology is available commercially, it is difficult to find related performance measurements in the open literature.

In high-power applications, the single-channel waveguide rotary joint consists of three E-plane waveguide rings of equal diameter, stacked "coaxially" with their narrow walls in contact, e.g., [1]. The center ring is halved along its E-plane so that its upper half can be brazed to the output ring and its lower half to the input ring. These two parts are separated by a 0.1-mm gap to avoid friction and wearing of the rings during rotation. As is typical for E-plane structures, this separation does not affect the fundamental-mode field configuration in the center waveguide. In order to couple power from the input to the center ring and further to the output ring, a series of apertures are used. The rings form two stacked 0-dB directional couplers, which can be designed, e.g., according to [2] and [3], thus, providing full power transfer from the input to the output via the center ring. Matched terminations are incorporated at the ends of the outer rings.

However, in order to perform the full power transfer through the three waveguide rings, the phase relations have to satisfy a 360° phase shift along the mean ring length. As the ring diameter is usually specified through other dimensions of the microwave system, provisions for phase adjustments must be incorporated.

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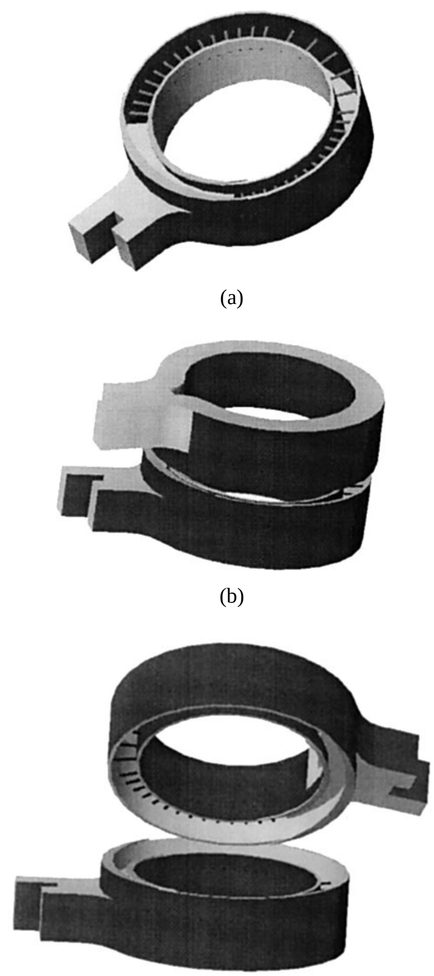

(a)

(b)

(c)

Fig. 1. Compact rotary joint utilizing ridged waveguides to lower the ring diameter. (a) One half of rotary joint. Parts aligned in the: (b) 0° and (c) 180° positions.

Therefore, this paper proposes a new rotary joint design, which, through the incorporation of ridges in the central ring, allows the phase to be adjusted for a given ring diameter. Two pairs of a tapered double-ridge section are introduced in the central waveguide such that one half moves with the upper and the other half with the lower part of the rotary joint. This is depicted in Fig. 1.

In the following, we will describe some of the fundamental design considerations and demonstrate that with this design, insertion losses below 1 dB can be achieved over a reasonable bandwidth.

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II. Design Considerations

A. Transmission Characteristics

The central ring is one of the important parts of the rotary joint. It is a continuous rectangular waveguide ring with apertures (coupling slots) on both of its narrow walls for full power coupling. As a first approximation, we will treat it as a periodic structure considering the middle ring as the unit segment of an infinitely loaded line. Each unit cell consists of a length $L = \pi D$, where D is the mean diameter of the ring. When the signal is coupled from the input ring to the center ring, the power transfer to the output ring will not be completed after one revolution of the wavefront. Thus, for maximum power transfer from the input ring to the center ring, the traveling wave after one revolution must be in phase with the incoming signal. This is possible if

$$\pi D = n\lambda_g \tag{1}$$

where λ_g is the guided wavelength. A different situation arises when

$$\pi D = \left(n \pm \frac{1}{2}\right)\lambda_g. \tag{2}$$

In this case, the traveling wave has a 180° phase difference after the first revolution. Thus, (1) and (2) give rise to the passband and stopband of the rotary joint [1].

The effect of slotting a waveguide is an increase of the guided wavelength. Consequently, the propagation constant β is much lower than in a regular waveguide, and the diameter of the ring required to achieve 2π radians of phase shift will be very high, thus leading to a large and bulky component. In order to arrive at a more compact design, we introduce ridged sections in the center waveguide ring. This measure increases β to very high values so that 2π radians of phase shift can be achieved with a reasonable ring diameter. (Alternatively and without ridges, the ring would not accomplish 360° of phase shift, which usually creates small stopbands within a specified passband frequency range [1].)

The entire design of the rotary joint can be made symmetric over its principal diagonal plane. The required phase conditions and aperture positions on the narrow walls of the center waveguide will vary with rotation. The required phase in the center waveguide for one revolution of the field will be $(360 - \psi)^\circ$, where ψ is the angular separation between input and output ports. A good design requires these conditions to be satisfied at all angular positions, which can be achieved by the effective use of ridge dimensions and aperture widths.

Since the entire component is symmetric, matching the phase condition between $\psi = 0^\circ$ and $\psi = 180^\circ$ is sufficient. The 0° position is shown in Fig. 2(a). Once the wave completes one revolution in the center ring, it will have a phase change of $\varphi_1 + \varphi_2$, where φ_1 and φ_2 are the phases in regions 1 and 2, respectively. In region 2, the center waveguide has apertures on both of its narrow walls, and they are designed for full power coupling (see Section II-B). Therefore, the traveling wave has 45° phase shift over region 2. The dimensions of the ridges are designed such that the phase changes by 315° in region 1. The extension of the ridges into the coupling region can be taken into account by adding the respective phases.

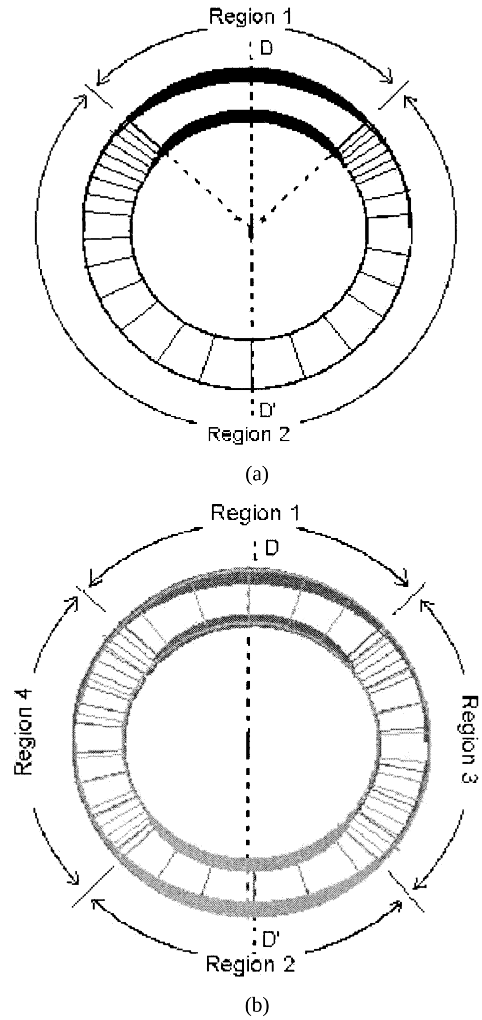

Fig. 2. Aperture and ridge configurations in the: (a) 0° and (b) 180° positions.

Fig. 2(b) shows the configuration in the 180° position. Here, the required phase for full power transfer from input to output is 180°. The configuration is symmetric with respect to plane DD'. Let φ_1 be the phase change over region 1 where the center waveguide has apertures on only one of its narrow walls. Let $\varphi_2 = (\phi_2)/4$ be the phase change over region 4, where ϕ_2 is the phase difference between even and odd modes due to apertures on one side in region 4. Thus, for phase matching in this position, we require

$$2(\varphi_1 + \varphi_2) = \pi. \tag{3}$$

Similarly, the phase can be matched in other positions. It is possible to match the phase for a few angular positions manually. Optimization might be used to further improve the performance.

B. Coupler Design

Since, unlike the input and output rings, the center waveguide ring has apertures on both of its narrow walls, the guided wavelength in all the three rings is not the same. To adjust the guided wavelength in the center ring, its broad wall dimension must be

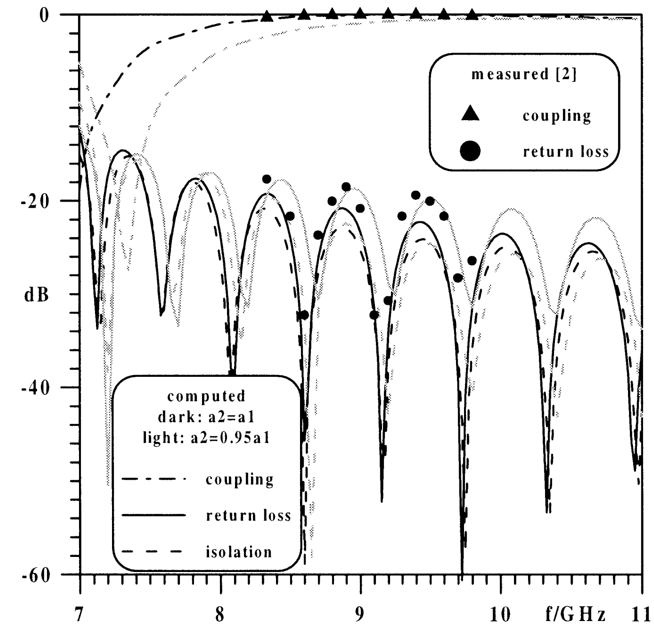

Fig. 3. Computed and measured [2] response of a 0-dB H-plane coupler with 22 apertures (21 pins). Dark lines are calculated with identical widths in main and coupled ports $(a_2 = a_1)$, gray lines are calculated with coupled port dimension reduced by 5% $(a_2 = 0.95a_1)$.

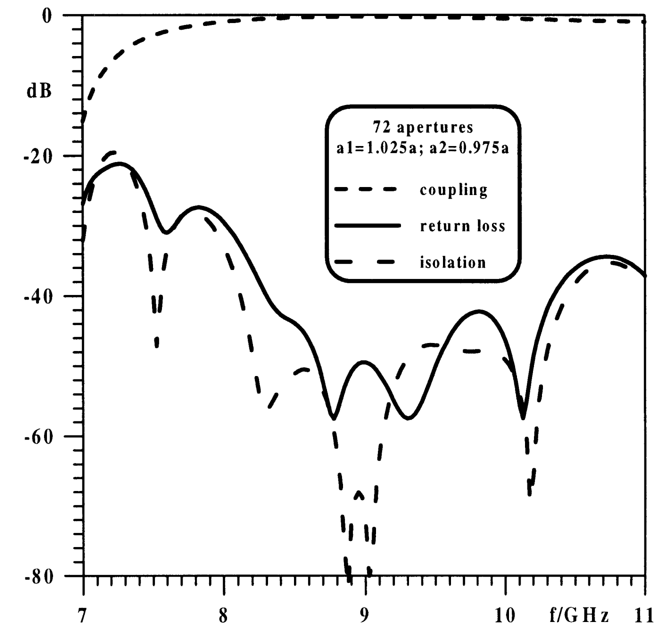

Fig. 4. Computed response of a 0-dB H-plane coupler with 72 apertures (71 pins) for the 8.8–9.2-GHz frequency range. Main and coupled port widths have been offset each by 2.5% in opposite directions.

slightly reduced. This places a restriction on the design of the 0-dB coupler.

For this purpose, a modified algorithm based on the mode-matching technique (MMT) has been developed [3], and initial coupler values were obtained using principles described in [2] and [4]. Fig. 3 compares computed and measured [2] results for the 0-dB uniform-aperture coupler presented in [2]. Good agreement is obtained even though our model features a conversion [5] from the cylindrical pins used in [2] to rectangular cross sections in the MMT. The lighter lines in Fig. 3 demonstrate the influence of reducing the width of the coupled guide, i.e., the center ring in the rotary joint.

As is well known, couplers with nonuniform apertures can be synchronously tuned and achieve superior return-loss performance. Therefore, an H-plane coupler with 72 nonuniform apertures was designed for the rotary joint application. In order to adjust the guided wavelength in the center ring, its width is reduced by 2.5%, whereas those of the input/output rings are increased by the same amount. The computed performance of this coupler is shown in Fig. 4. In comparison with Fig. 3, it demonstrates the advantage of the nonuniform aperture design by achieving return-loss and isolation values better than 40 dB.

C. Ridge Waveguide Analysis

An accurate evaluation of the fundamental-mode phase constant in the ridged waveguide sections is of fundamental importance for this design. Due to rotation of the two rotary joint parts (c.f. Fig. 1), symmetric as well as asymmetric ridged waveguide cross sections appear. A snapshot cross section is shown in Fig. 5

In order to determine the fundamental-mode phase constants of cross sections pertaining to the rotary joint, a versatile and efficient routine was recently developed by one of the authors [6].

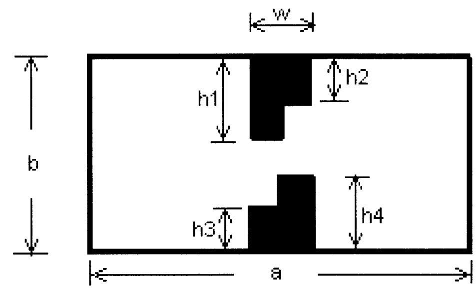

Fig. 5. Snapshot of ridged waveguide cross section obtained by rotation of two halves shown in Fig. 1.

TABLE I
CUTOFF WAVENUMBERS OF RIDGED WAVEGUIDES IN FIG. 5 CALCULATED USING TRANSVERSE RESONANCE TECHNIQUE [6] AND HFSS. $a = 22.86$ mm, $b = 10.16$ mm, AND $w = 4.0$ mm. DIMENSIONS ARE IN MILLIMETERS; k_c IS IN RADIANS PER MILLIMETER

h_1	h_2	h_3	h_4	k_c [6]	k_c (HFSS)
3	2	2	3	0.10615	0.10904
3	3	2	2	0.11062	0.10983
3	3	3	3	0.10216	0.10199
2	3	2	3	0.10551	0.10766

The procedure is based on a transverse resonance technique utilizing well-known susceptance relations for the cross-sectional discontinuities introduced by the ridges [7]. For details on the theory and general results, the reader is referred to [6]. Here, we are demonstrating the validity of this approach with respect to the specific cross section of Fig. 5. A comparison of the results computed by this technique with those obtained by the commercial package HFSS is shown in Table I and demonstrates good agreement.

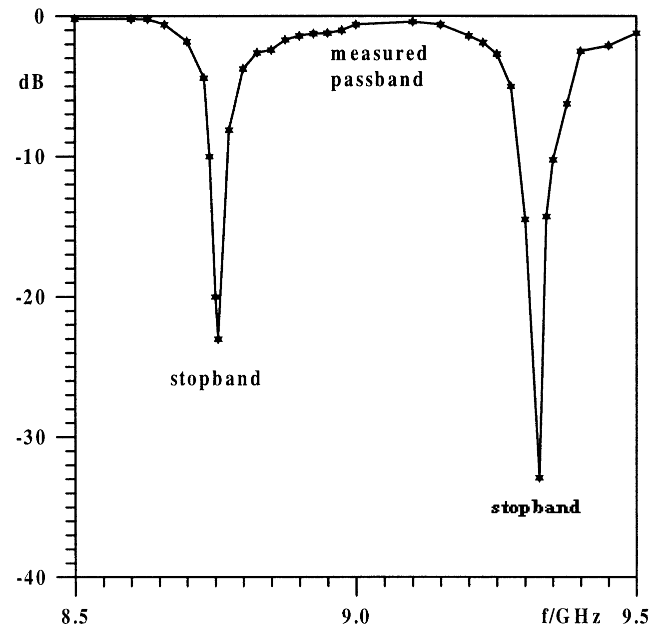

Fig. 6. Measured passband and stopbands of waveguide rotary joint prototype in the 0° position.

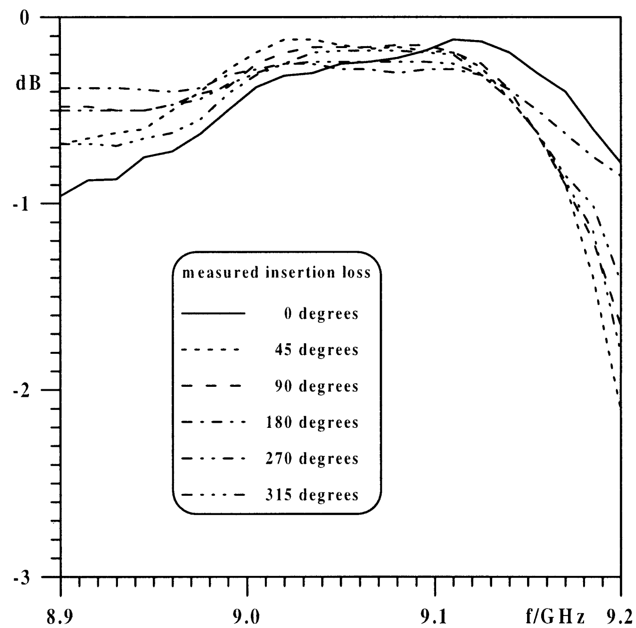

Fig. 7. Measured insertion-loss performance of rotary joint prototype in various angular positions.

III. Results

Using the guidelines presented above, a single-channel waveguide rotary joint was designed for operation at 9.05 GHz. The mean diameter of the rotary joint was specified as 119.38 mm (4.7 in). A total of 72 nonuniform coupling apertures are employed for full power coupling. The diameter of the grid wire (coupling pins) is 0.5 mm. The center waveguide broad wall is undercut by 2.5%; input/output rings are widened by 2.5% in order to adjust the guided wavelength in the three rings. The peak heights of the ridges are 2.2 mm and their thickness is 2.0 mm in one-half of the rotary joint.

The center ring is halved along the central axis of the transverse cross section. The upper and lower halves of the center ring are brazed to the output and input rings, respectively. The so-obtained upper and lower halves of the rotary joint are separated by a 0.1-mm ball-bearing structure. This separation avoids friction and wearing of the rings and has negligible effect on the field configuration in the center waveguide for fundamental mode operation. In general, waveguide rotary joints have long-life rubber seals to protect the inside of the waveguides and the ball bearings from humidity and dust.

Fig. 6 shows the measured transmission characteristic of the rotary joint in the 0° position. The passband is centered at 9.05 GHz with stopbands appearing at 8.75 and 9.33 GHz.

Measurements of the insertion loss at different angular positions are presented in Fig. 7. The measured insertion loss is better than 1 dB between 8.9–9.17 GHz. It is expected that the bandwidth may be improved by optimizing the aperture widths and ridge dimensions for the required phase match in different angular positions.

In order to ensure high-power-handling capability, the prototype rotary joint was tested at a peak power of 100 kW. The final design is supposed to operate up to 250 kW.

Transition phase responses of the input and output couplers are linear with respect to frequency. Therefore, although the absolute phase value changes in the individual positions measured in Fig. 7, the frequency linearity is preserved. As the joint rotates with only 44 r/min, the influence of the rotation on the phase linearity is of no concern.

IV. Conclusions

It has been demonstrated that by incorporating ridge-waveguide sections, a single-channel waveguide rotary joint can be designed, which simultaneously achieves high-power-handling capability, reduced component size, and correct signal phase conditions. The presented design guidelines demonstrate the feasibility of this concept. Prototype measurements validate the design approach.

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