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Broadband Coaxial Rotary Joint With Simple Substrate Integrated Waveguide Feeder

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ABSTRACT This paper presents a broadband coaxial rotary joint with simple single-layer substrate integrated waveguide (SIW) feeder. The annular slot etched on the surface of SIW can effectively convert TE_{10} mode in the rectangle SIW into the rotational symmetric TEM mode in the coaxial line. Broadband impedance matching can be achieved because the additional capacitive coupling between the short-circuited circular metallic patch and coaxial line. Comparing with previous SIW fed rotary joints, the proposed design has the advantages of wider bandwidth and simpler feeding structure. The equivalent circuit is given to explain the design. A prototype centered at 12 GHz is fabricated with the 10-dB impedance matching bandwidth of 24.9% and the minimum insertion loss of 0.3 dB.

INDEX TERMS Broadband, coaxial rotary joint, coupling, single-layer substrate integrated waveguide.

I. INTRODUCTION

The rotary joint is a kind of microwave device that realizes the normal transmission of the signal during rotation. It is widely used in the radar with mechanical beam scanning, vehicular systems and satellite communication system on the move. In previous designs, different structures are applied to feed the rotary joint, such as rectangular waveguide [1]–[8], annular ring waveguide [9], stripline [10] and coaxial line [11]. However, these feeder structures are large size and difficult to be integrated with the substrate integrated waveguide (SIW) circuit. The SIW fed rotary joint can share the advantages of SIW such as small size, easy integration, and small loss at high frequency.

Two SIW fed rotary joint have been reported [12], [13]. The first SIW fed rotary joint [12] is achieved by inserting SIW probe into the circular waveguide and exciting TM_{01} mode, but the relative bandwidth is just 9%. To improve the bandwidth, the perpendicularly positioned double-layer SIW feeder with two magnetic current loops [13] is utilized to excite TM_{01} mode in the circular waveguide, and a relative bandwidth of 11.1% is obtained.

In this letter, a single-layer SIW feeder with the asymmetric annular slot and the shorted circular patch is utilized to excite TEM mode of a coaxial main body. The choke groove on the inner conductor needed by the traditional coaxial rotary joint [14] is avoided. A physics-based equivalent circuit is given for interpreting the working mechanism. Parametric study and design procedure are given to guide the proposed design.

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II. PROPOSED SIW FED COAXIAL ROTARY JOINT

A. CONFIGURATION

Fig. 1 shows the configuration of the proposed SIW fed coaxial rotary joint, which consists of two parts, the SIW feeder and the coaxial main body. The SIW feeder has an arc-shaped surface at the end of SIW, and the asymmetric annular slot and a shorted circular patch on one metal surface are at quarter-wavelength from the arc-shaped surface. The coaxial main body consists of outer and inner conductor as the coaxial line, an annular choke groove on the outer conductor, and two dielectric annular support to fix the inner conductor. The choke groove maintains electric continuity at the separated position of the outer conductor. The substrate of SIW feeder is RO4003C with dielectric constant of 3.38, thickness of 1.524 mm and loss tangent of 0.0027. The metal in the proposed rotary joint is copper and the material of the dielectric annular support is Teflon with dielectric constant of 2.1, thickness of 2 mm and loss tangent of 0.0002.

The two SIW feeders are vertically fixed to the coaxial main body and remain face to face. There is a gap between

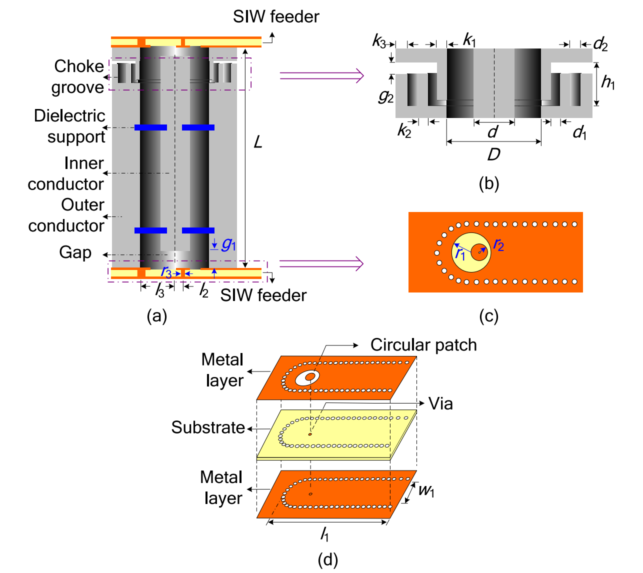

FIGURE 1. **Configuration of the proposed SIW fed coaxial rotary joint. (a) The overall structure. (b) The part of coaxial rotary with choke groove. (c) The top view of SIW feeder. (d) The 3-dimensional view of SIW feeder.**

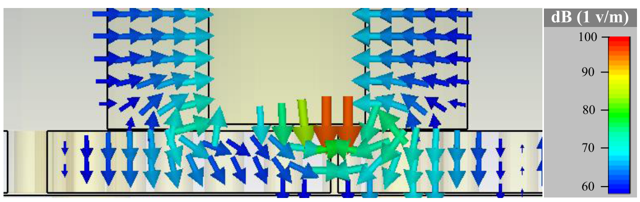

FIGURE 2. **Simulated *E*-field distribution near the connection surface of the SIW feeder and the coaxial line at 12.2 GHz.**

the two ends of the inner conductor and the surface of SIW feeder. The centers of outer circle of the two annular slots and the center of inner conductor are on a straight line. In such configuration, the TE_{10} mode signal in SIW will be converted into the TEM mode signal in the coaxial main body, as shown in Fig 2. It can be seen from Fig. 2 that the annular slot and shorted circular patch produce horizontal electric field from TE_{10} mode signal. This horizontal electric field can excite the TEM of coaxial line by the coupling between the shorted circular patch and inner conductor of coaxial line. Wide impedance matching bandwidth can be achieved when this coupling is strong.

B. EQUIVALENT CIRCUIT

The equivalent circuit of the proposed SIW fed coaxial rotary joint is given in Fig. 3(a) [15], [16]. The inductor L_v is adopted to present the effect of the via connected to the circular patch. The capacitors C_{sp} and C_{si} are used to describe the coupling between the asymmetric annular slot and the circular patch and between the asymmetric annular slot and inner conductor, respectively. C_{pi} represents the capacitive coupling between the shorted circular patch and inner conductor. The transformer n_1 represents the coupling between the SIW feeder and the coaxial main body. θ_1 and Z_g are the electrical

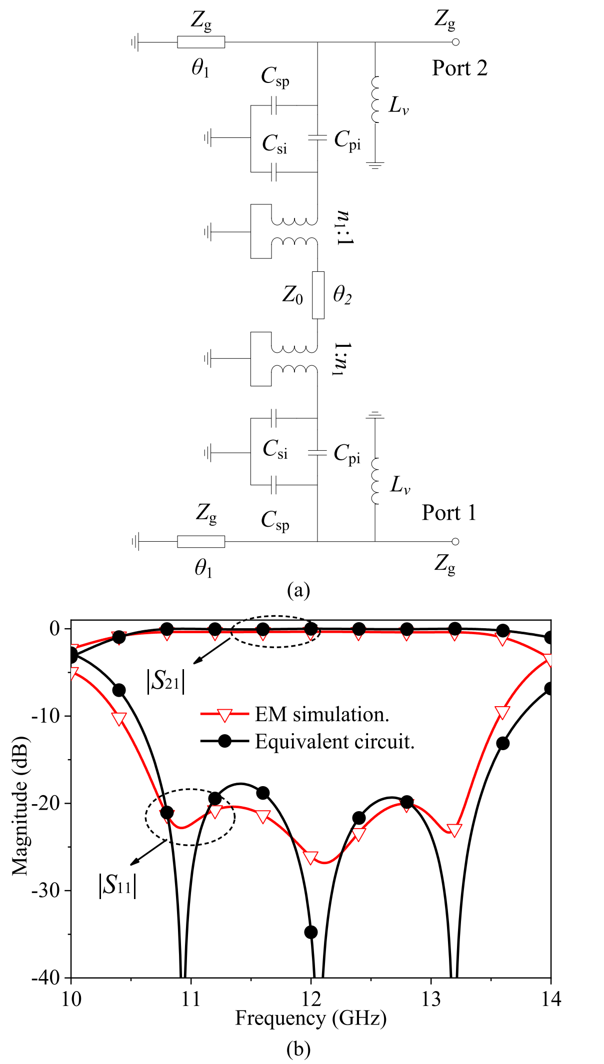

FIGURE 3. **Equivalent circuit and its simulated results of the proposed SIW fed coaxial rotary joint. (a) Equivalent circuit. (b) Simulated results.**

length and the characteristic impedance of the SIW between the center of asymmetric annular slot and the arc-shaped shorted surface, respectively. θ_2 and Z_o are the electrical length and the characteristic impedance of coaxial main body, respectively.

Z_0 of coaxial main body is set to 50 Ω because this impedance value takes the power capacity, voltage endurance and loss of coaxial line into consideration. θ_2 is set to 720° to suppress the reflection and the high-order mode of the coaxial line because θ_2 with an integer multiple of $\lambda_g/2$ can make the proposed rotary joint obtain the minimum reflection and the sufficient length of coaxial line can get enough attenuation of the high-order mode (TE_{11} mode) in the coaxial line. θ_1 is set to 90° to obtain strong electric field around the asymmetric annular slot. Z_g should ensure the operating frequency range of the rotary joint to be inside the single-mode operating range. For example, Z_g = 193 Ω if single-mode operating range is from 9 GHz to 18 GHz. Then, if C_{sp} = 0.016 pF, C_{si} = 0.002 pF, C_{pi} = 0.122 pF,

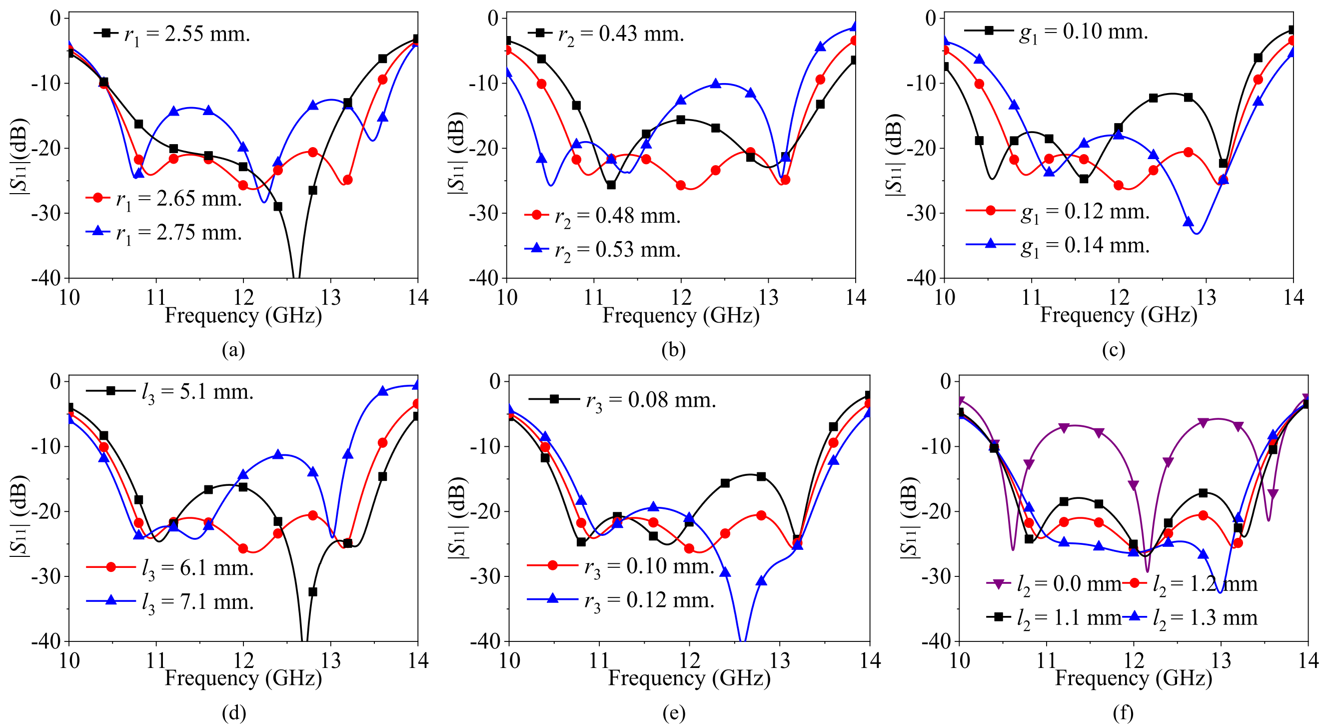

FIGURE 4. **Simulated responses of proposed SIW fed coaxial rotary joint with different (a) r_1, (b) r_2, (c) g_1, (d) $l3$, (e) r_3, and (f) l_2. (r_1 = 2.65 mm, r_2 = 0.48 mm, g_1 = 0.12 mm, l_3 = 6.1 mm, r_3 = 0.1 mm and l_2 = 1.2 mm).**

L_v = 1.68 nH and n_1 = 1.14, the simulated results of the equivalent circuit agree well with the results of electromagnetic (EM) simulation as shown in Fig. 3(b).

C. PARAMETER CONSIDERATION AND PARAMETRIC STUDY

The diameters (d and D) of the 50-Ω coaxial line should take into account the coupling between SIW feeder and coaxial line and ensure only TEM mode in coaxial line within the operating bandwidth, where C_{si} and n_1 both decrease with d and the cut-off wavelength of TE_{11} mode increases with $d + D$.

For the choke groove, it is just on the outer conductor, which is enough to ensure the rotation and electric continuity of the coaxial main body because the inner conductor is coupled to the SIW feeder. The choke groove is wideband [14] and the dimensions are shown as follows: d_1 = 1 mm, d_2 = 2.4 mm, k_1 = 1 mm, k_2 = 1 mm, k_3 = 1.5 mm, g_2 = 0.5mm and h_1 = 6 mm.

For the coupling structure between SIW and coaxial line, the parametric study based on the performance of the proposed design is shown in Fig. 4. Figs. 4(a) and 4(b) exhibit that the bandwidth increases with r_1 or r_2, but the level of impedance matching becomes better first and then worse because n_1 and C_{si} both increase with r_1 and C_{pi} increases with r_2. Figs. 4(c) and 4(d) show that the bandwidth decreases with the increase of g_1 or l_3, while the level of impedance matching becomes better first and then worse because C_{pi} decreases with the increase of g_1 and θ_1 increase with l_3. As shown in Figs. 4(e) and 4(f), r_3 and l_2 mainly have effect on the level of impedance matching, and the impedance matching becomes better first and then worse with the increase of r_3, but becomes better with the increase of l_2. This is because L_v decreases with the increase of r_3, C_{sp} increases with l_2, and C_{pi} decreases with the increase of l_2.

D. DESIGN PROCEDURE

For the SIW fed coaxial rotary joint, the design procedure is summarized as follows:

Step 1: Set $\theta_1 = 90°$, $Z_g = 193$ Ω, $\theta_2 = 720°$, $Z_0 = 50$ Ω. The initial d = 4 mm and D = 9.2 mm according to the equivalent circuit and parameter consideration. In such case, the cutoff frequency of the high-order mode (TE_{11} mode) of the coaxial line is 14.47 GHz, which is higher than the upper edge of the operating frequency range in Fig. 3.

Step 2: Get the initial r_1 = 2.65 mm, r_2 = 0.48 mm, g_1 = 0.12 mm, l_3 = 6.1 mm, r_3 = 0.1 mm and l_2 = 1.2 mm of the coupling structure in accordance with variation rule of the parametric study in Fig. 4.

Step 3: Get the final performance by slightly optimize the dimensions in EM simulation using Computer Simulation Technology (CST).

III. RESULTS

A prototype of the proposed SIW fed coaxial rotary joint with the center frequency of 12 GHz is demonstrated. Figs. 5(a) and 5(b) show the photograph of the prototype and the choke groove, respectively, where tapered

TABLE 1. Performances comparison between previous rotary joint and the proposed design.

Ref.	f_0 (GHz)	10-dB FBW (%)	Insertion loss (dB)	Feeder type	Height (mm)	Radius (mm)
[1]	33	4.5	0.4-0.8	Rectangular waveguide	NA	NA
[9]	9.5	9.3	0.25-1.02	Annular waveguide	NA	NA
[12]	12	9	0.35-1.12	Single-layer SIW	80	14
[13]- I	11.77	6.1	0.31-1.19	Single-layer SIW	26.1	14
[13]- II	11.75	11.1	0.25-1.09	Dual-layer SIW	21	13.5
Proposed design	12	24.9	0.3-0.8	Single-layer SIW	52	4.6

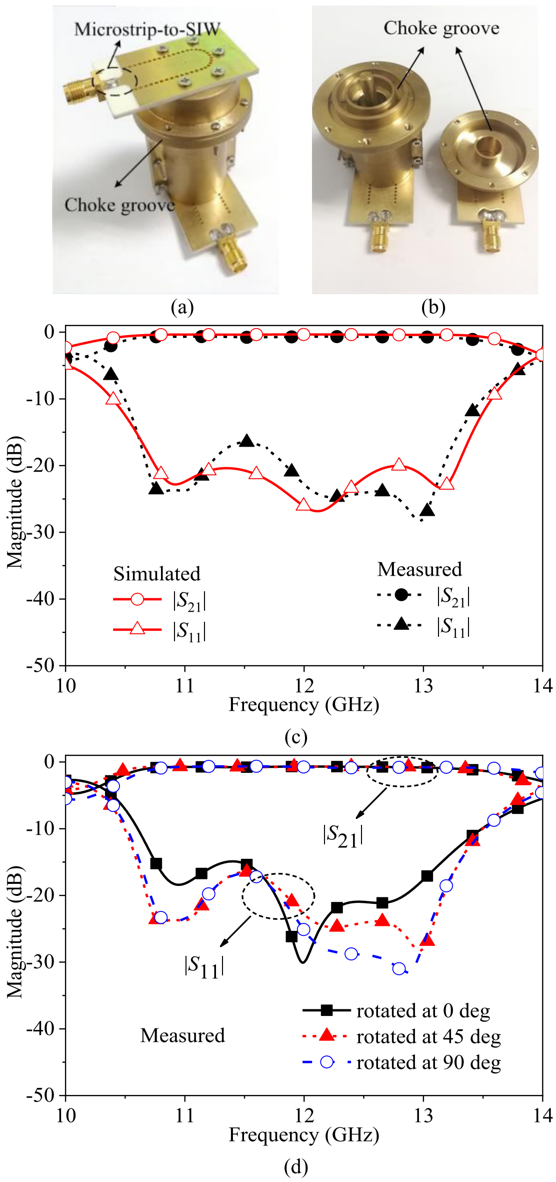

FIGURE 5. The photograph and results of the proposed SIW fed coaxial rotary joint. (a) The photograph of coaxial rotary joint. (b) The photograph with choke groove. (c) Simulated and measured results at 45°. (d) Measured results at different angles e photograph and results of the prototype.

Microstrip-to-SIW transition is utilized to feed the SIW feeder [17]. According to the design procedure, the final dimensions are obtained as follows: $d = 4$ mm, $D = 9.2$ mm, $L = 52$ mm, $w_1 = 9$ mm, $l_1 = 20$ mm, $l_2 = 1.2$ mm, $l_3 = 6.1$ mm, $r_1 = 2.65$ mm, $r_2 = 0.48$ mm, $r_3 = 0.1$ mm, and $g_1 = 0.12$ mm. Here, the dimensions of choke groove have been given in Part C of Section II. The measurement is carried out on the two-port Keysight N5230C vector network analyzer.

Fig. 5 shows the simulated and measured results of the proposed coaxial rotary joint at different angles. It can be found from Fig. 5 that the performances agree well with each other when the proposed rotary joint is at different rotating angles. The measured 10-dB fractional bandwidth is from 10.63 GHz to 13.66 GHz or 24.9 % at the center frequency of 12 GHz. The minimum insertion loss is 0.3 dB.

The main performances of several rotary joints fed by different structures are compared in Table 1. Compared with the SIW fed rotary joints [12], [13], the proposed design has the advantages of wide bandwidth, simple structure of SIW feeder and small radius of rotating main body. Compared with rotary joints using other feeding structures [1] and [9], this design is easy to integrate with SIW circuits of SIW system.

IV. CONCLUSION

In this letter, a broadband coaxial rotary joint is proposed by using the single-layer SIW feeder with an asymmetric annular slot and a shorted circular patch. The features of wide bandwidth, simple SIW feeder structure, small radius of rotating main body and low insertion loss can be achieved. Stable performance can be obtained when rotating. Therefore, the proposed SIW fed coaxial rotary joint is believed to be benefit to the development of rotary joint in microwave system.

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