Design of Compact Waveguide Twists

Pedro I. Alonso-Juaristi, Jaime Esteban, and Jesús Mª Rebollar

***Abstract*—A new geometry for compact twist components composed of rectangular and circular waveguide sections is presented. The proposed twist geometry presents several advantages: 1) it can be designed for any rotation angle; 2) it is extremely short and, therefore, well suited for satellite communication applications; 3) its electrical behavior is excellent for either narrow or broad frequency bands; and 4) a very accurate and efficient full-wave mode-matching method can be used to analyze these twists. A software package has been developed to design the proposed compact twist structure in a full-wave method.**

***Index Terms*—Circular waveguide, generalized scattering matrix, mode matching, rectangular waveguide, twist.**

I. Introduction

COMPACT rectangular-waveguide twist components are required in many communication applications, especially for satellite communications.

Twists used in this kind of device are constructed mechanically by twisting a suitably warmed length of the conventional rectangular waveguide an adequate angle between the input and output waveguides. This procedure results in a relative large twist; moreover, it may not be convenient because of mechanical stresses, especially on satellite communication components aboard spacecrafts.

One of the first references that considers the analysis of this kind of devices is [1], where the commercial software HFSS [three–dimensional (3-D) finite-element method (FEM)] is used. More recently, Bonermann [2] has proposed a new type of twist of smaller dimensions than previous ones. However, these twists present important limitations, for example, the imposed 90° rotation, or its relative narrow frequency-band features.

In this paper, a new compact twist geometry is proposed which presents greater similarity with classical twists since the rotation between input and output is gradually performed. This new structure is based on the combination of circular and rectangular waveguide sections gradually rotated until the desired rotation angle between the input and output rectangular waveguides is reached. The proposed structure can be rigorously and very efficiently analyzed by the full-wave mode-matching technique.

A brief description of the theory employed is presented. The design and optimization of some different twists have been carried out to check their features. Finally, a compact 90°-twist has been implemented and measured in order to show the accuracy of the software developed and the performance achieved by the proposed twist structure.

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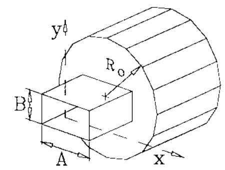

Fig. 1. Circular–rectangular waveguide junction.

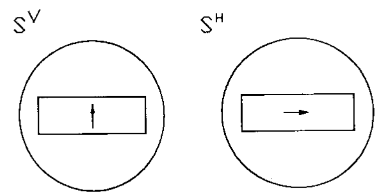

Fig. 2. Vertical and horizontal polarizations in the rectangular–circular discontinuity.

II. Theory

A. Basic Discontinuity

The twist structure proposed in this paper consists of connections of multiple discontinuities between rectangular and circular waveguides; therefore, the first step to analyze it is to develop a multimode characterization of these discontinuities (see Fig. 1).

Only very recently, and in spite of the extensive use of this discontinuity in different microwave components, has it been accurately characterized by means of the mode-matching method [3]. It is worth mentioning that all the cross-couplings integrals needed to analyze this discontinuity are analytically evaluated, so that an important central processing unit (CPU) time reduction without loss of accuracy can be achieved in the implementation of this technique.

Considering both polarizations (vertical and horizontal, i.e., TE_{10} and TE_{01} modes in the rectangular waveguide, respectively) as two electrical ports, the rectangular–circular discontinuity is a four-port structure and can be fully described by its generalized scattering matrix (GSM) of generalized two-port discontinuity. This procedure is advantageously exploited with an adequate mixing of the GSM's, $S^{\rm V}$ and $S^{\rm H}$, for the vertical and horizontal polarizations [4] (see Fig. 2).

The GSM of the generalized two-port S of the basic discontinuity, considering both polarizations, can be written

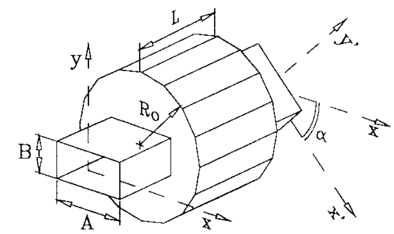

Fig. 3. The basic block for the proposed structure consisting of two rectangular waveguides rotated at an angle α and a short section of circular waveguide.

in the following way:

$$S = \left[\begin{array}{ccc|ccc} S_{11}^{\mathrm{V}} & \vdots & 0 & S_{12}^{\mathrm{V}} & \vdots & 0 \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ 0 & \vdots & S_{11}^{\mathrm{H}} & 0 & \vdots & S_{12}^{\mathrm{H}} \\ \hline S_{21}^{\mathrm{V}} & \vdots & 0 & S_{22}^{\mathrm{V}} & \vdots & 0 \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ 0 & \vdots & S_{21}^{\mathrm{H}} & 0 & \vdots & S_{22}^{\mathrm{H}} \end{array}\right] \tag{1}$$

where $\mathbf{0}$ is the zero matrix.

B. Basic Block for the Proposed Twist Geometry

Fig. 3 shows the basic block for the proposed twist. It consists of two circular–rectangular waveguide junctions at an angle α linked by the circular waveguide section of radius R_0 and length L.

Let S^{I} and S^{II} be the GSM's of the two discontinuities referred to their own coordinate systems x–y and x'–y'. To obtain the overall GSM S^T for this basic block, the GSM of the second discontinuity, S^{II}, must be rotated an angle α before being combined with the S^{I} of the first junction. To do this, the relationship between the modes of the common circular waveguide expressed in both reference systems must be taken into account. After some simple algebraic manipulations, the rotated GSM of the second junction, SR^{II}, can be expressed in terms of the previous GSM, S^{II}, and the rotation matrix G, by means of the following expressions [4]:

$$\begin{aligned} SR_{11}^{\mathrm{II}} &= GS_{11}^{\mathrm{II}}G^T \\ SR_{21}^{\mathrm{II}} &= S_{21}^{\mathrm{II}}\ G^T \\ SR_{12}^{\mathrm{II}} &= GS_{12}^{\mathrm{II}} \\ SR_{22}^{\mathrm{II}} &= S_{22}^{\mathrm{II}} \end{aligned} \tag{2}$$

where G^T is the transpose of matrix G. The rotation matrix G can be expressed as

$$G = \left[\begin{array}{c|c} G_1 & G_2 \\ \hline -G_2 & G_1 \end{array}\right] \tag{3}$$

where G_1 is a diagonal matrix whose elements are $\cos n\alpha$, G_2 is a diagonal matrix whose elements are $(-1)^{(n-1)/2} \sin n\alpha$, and n is the angular variation of the corresponding mode ($\mathrm{TE}_{p,n}/\mathrm{TM}_{p,n}$).

Finally, the overall GSM of this basic block is obtained in a classical way by combining the GSM's of the generalized two-port discontinuities S^{I} and SR^{II} [5].

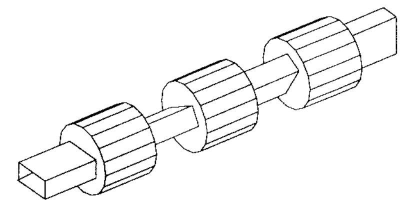

Fig. 4. 90°-twist composed of three basic blocks.

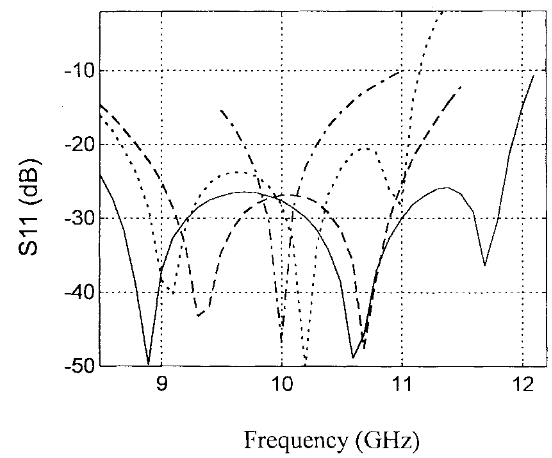

Fig. 5. Magnitude of S_{11} (dB) parameter versus frequency (GHz) for optimized 90°-twist with different numbers of basic blocks: (two, dashed–dotted line), (three, dashed line), (four, dotted line). (five, solid line).

C. Proposed Twist Structure

The proposed twist can be considered as a combination of the above-described basic blocks, each with a rotation angle α to achieve the desired total rotation between the input and output rectangular waveguides. If the total rotation angle is α_T, the rotation angle α of each block is α_T/N, where N is the number of basic blocks.

As an example, Fig. 4 shows a 90°-twist, consisting of three basic blocks, each one with a 30° rotation angle. The overall GSM for the whole twist is obtained by a combination of the GSM's of the basic blocks in a similar way to the one mentioned above [5].

III. Compact 90°-Twist: Design and Optimization

In order to check the main features of the proposed twist structure, the design of a 90°-twist has been carried out.

90°-twists with different number of basic blocks have been optimized by means of the full-wave analysis method described above and the minimization routine described in [6]. All the considered twists have been optimized to achieve 20-dB return loss over as broad a frequency band as possible.

Only the lengths of the rectangular and circular waveguide sections have been considered as geometric variables to be optimized. The dimensions A and B of the rectangular waveguide cross sections are 22.86 mm, 10.16 mm, and the radius R_0 of the circular waveguide is 12.51 mm. Fig. 5 displays the optimized return losses for four different twists consisting of either two, three, four, or five basic blocks. A summary of

TABLE I

Number of basic blocks	20dB return-loss bandwidth(%)	Length/λg (10 GHz)
2	7	0.35
3	23	0.58
4	26	0.69
5	35	0.82

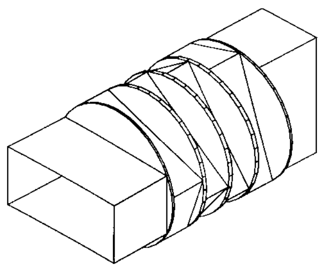

Fig. 6. Optimized 90°-twist with five basic blocks.

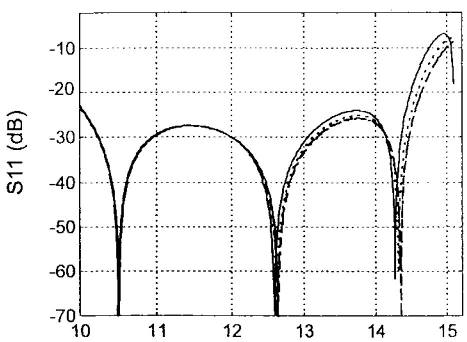

Fig. 7. Convergence of S_{11} (dB) as a function of the number of modes. Rectangular 20 (TE + TM) Circular 39 (TE + TM) (solid line). Rectangular 30 Circular 58 (dashed line). Rectangular 40 Circular 78. (dotted line). Rectangular 50 circular 98 (dashed–dotted line).

the main features for these optimized twists is presented in Table I.

It is observed that increasing the number of basic blocks provides an enlarged bandwidth.

An optimized 90°-twist with five basic blocks for *Ku* band (central frequency 12.5 GHz) has been optimized and manufactured. Rectangular waveguide WR75 and a circular waveguide with a radius of 10.65 mm have been employed. The total length of the optimized twist is 0.9 λ_g (at 12.5 GHz). Fig. 6 shows its final shape.

To check the convergence of both the method and the software developed, the return loss of this five basic-block twist has been computed for different numbers of TE and TM modes in the rectangular and circular waveguide sections. In order to avoid relative convergence phenomena, a ratio between the total number of modes in the rectangular and circular waveguide sections equal to the ratio between their cross-section areas has been employed. Fig. 7 illustrates the magnitude of S_{11} versus frequency for different combinations

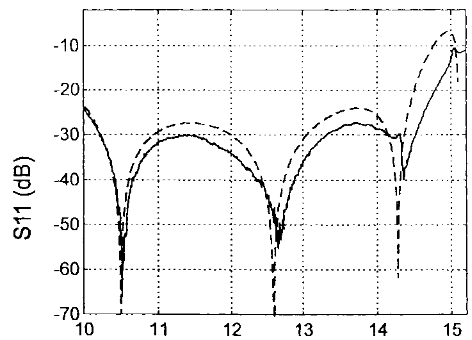

Fig. 8. Magnitude of S_{11} (dB) versus frequency (GHz). Experimental results (solid line). Numerical results (dashed line).

of modes. A good convergence behavior can be observed from this figure. This conclusion is very important because a small number of modes can be used in the analysis of the twist, thus minimizing the CPU time used during the design process.

Fig. 8 displays the numerical and experimental return loss of the manufactured twist, where a return loss better than 20 dB over a 37% frequency bandwidth has been achieved.

Close agreement can be observed between the numerical and experimental results. The slight differences between both results can be attributed to manufacturing tolerances.

IV. Conclusion

A new geometry for compact twists for any rotational angle has been proposed and a full-wave mode-matching technique has been presented for the analysis of this kind of twist. The results presented show useful features of the proposed twist structure for narrow and broad-band applications.

The efficiency and accuracy of the software developed have been checked by comparing the numerical and experimental results for a compact 90°-twist. The excellent electrical performance and a small size of this twist is well-suited for satellite communications applications.

References

[1] B. M. Dillon, A. A. P. Gibson, R. Aitmehdi, and A. K. Brown, "Design of an orthomode launcher using finite element CAD software," in *Proc. Int. Conf. Antennas Propagat.*, vol. ICAP-93, Edinburgh, Scotland, U.K., Apr. 1993, pp. 837–840.

[2] J. Bonermann, "Design of integrated waveguide twist components," *Inst. Elect. Eng. Proc. Microwave Antennas Propagat.*, vol. 142, pp. 345–349, Aug. 1995.

[3] R. H. MacPhie, R. Deleuil, and A. K Daoudia, "Fullwave scattering analysis of the junction of a circular waveguide and a smaller rectangular waveguide," in *URSI Meeting*, Chicago, IL, 1992, p. 216.

[4] J. M. Rebollar, J. Esteban, and C. Vecino, "Rotation of rectangular waveguides by insertion of circular waveguides," in *Progress Electromag. Research Symp., PIERS-1994*, Noordwijk, The Netherlands, July 1994, pp. 184–187.

[5] J. M. Rebollar and J. A. Encinar, "Field theory analysis of multiport–multidiscontinuity structure: Application to short-circuited *E*-plane septum," *Proc. Inst. Elect. Eng.*, vol. 135, pt. H, no. 1, pp. 1–7, Feb. 1988.

[6] R. Fletcher and M. J. D. Powell, "A rapidly convergent descent method for minimization," *Comp. J.*, vol. 6, no. 2, pp. 163–168, 1963.

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