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Design and Implementation of a Compact 90° Waveguide Twist With Machining Tolerant Layout

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***Abstract*— We report on a novel compact wideband 90° twist with performance tolerant to small geometry variation and hence improved manufacturability through direct milling. The experimental verification shows 44% fractional bandwidth with return loss better than 20 dB over the 140–220 GHz band. The performance, compactness, and tolerance to manufacturing inaccuracy make it very suitable for use in various waveguide systems from microwave to millimeter-wave range.**

***Index Terms*— Compact waveguide twist, simplified manufacturing process, single-step twist.**

I. Introduction

WAVEGUIDE twists are essential interconnection parts in many millimeter and submillimeter systems, especially for modern polarization-sensitive terahertz (THz) receivers with state-of-the-art performance (e.g., [1], [2]). As minimization of the RF path and respective insertion loss for achieving the best noise performance is a key feature of such systems, a large diversity of single and multisteps' waveguide twists has been investigated to achieve compactness and low insertion loss with minimum reflections (e.g., [3]–[6]). Among the different types, 90° twists have been widely adopted in the field since the outputs of orthomode transducers (e.g., [7]) are generally orthogonal to each other. Commercially available solutions employed complex and time-consuming processes such as electroforming to produce continuous twists. This approach relies on gradually twisting a rectangular waveguide along its longitudinal axis [8]. A smooth rotation guarantees excellent matching and broadband operation. Unfortunately, such twists are not suitable for highly integrated and compact systems, since they require lengths of several wavelengths to work properly.

An alternative solution was explored in [9], where L-shaped cross sections were used to rotate polarization progressively. In [10], 90° rotation is accomplished through an L-shaped triple-mode quarter-wave transformer. These configurations are able to achieve good results over a limited fractional bandwidth of 20% [10].

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Color versions of one or more of the figures in this letter are available online at http://ieeexplore.ieee.org.

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As compactness is one of the major concerns for highly integrated systems (e.g., [1], [2]) most of the development has focused on step twists. The multistep structures proposed in [3]–[5] are formed by a series of waveguide sections with different rotation angles and thicknesses. The cross sections of each step could be rectangular [3], rounded wall [4], or other more complicated geometries [5]. These implementations are less bulky than continuous and L-shaped twists but yet are relatively complex in fabrication and not as compact as single-step twists.

Regarding single-step twists, cross sections based on corner cut waveguides have been extensively studied [6]. More complicated geometries with multiple sharp corners or ridge waveguides have been also proposed [11], [12]. These geometries introduce additional cuts in the twist aperture that maximizes bandwidth. Nonetheless, the behavior of such twists is usually rather sensitive to fabrication accuracy, which makes their performance somewhat unpredictable. Sharp corners of the twist aperture make simple fabrication techniques such as milling not practical. For instance, the design proposed in [12] is implemented using micromachining techniques from [13]. In [14], a twist design compatible with SU-8 photoresist-based all-metal micromachining is proposed [15].

In this letter, we present a novel single-step 90° twist, which combines a tolerant geometry with compactness and broadband performance at millimeter-waves. In contrast with previous designs existing in the literature, its smooth geometry considerably eases manufacturing through simple fabrication techniques, for example, direct milling, resulting in a more predictable performance.

II. Theory and Design

Fig. 1 gives an overview of the suggested twist layout. It comprises two half-circular apertures with radius R linked by a rectangular aperture defined with parameters A and B.

A. Principle of Operation

As was analyzed in [10], the insertion of a waveguide twist introduces discontinuities. When such discontinuities are separated by approximately a quarter guided wavelength ($\lambda_g/4$), their effects are mutually canceled. Therefore, the thickness of the twist should be close to $\lambda_g/4$ of the dominant mode inside the structure at the center frequency, that is, 660 μm for our design.

From the perspective of port 1, the dominant mode inside the twist transforms TE_{10} into TE_{01}. In Fig. 2(a), it is seen how

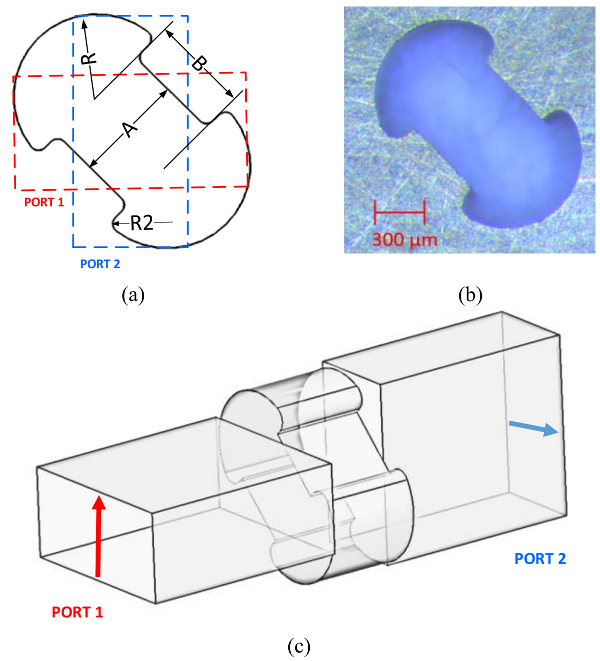

Fig. 1. Proposed waveguide twist. (a) Cross section view and waveguide ports. Dimensions for WR-5.1 band: $R = 460\ \mu$m, $A = 600\ \mu$m, $B = 500\ \mu$m, and $R2 = 100\ \mu$m. The thickness is 660 μm. (b) Photograph of the fabricated twist. Fabricated dimensions with precision $\pm 2\ \mu$m: $R = 468\ \mu$m, $A = 605\ \mu$m, $B = 503\ \mu$m, and $R2 = 103\ \mu$m. The measured thickness is 662 μm. The structure is incorporated in UG385/U standard flange. (c) Waveguide twist layout.

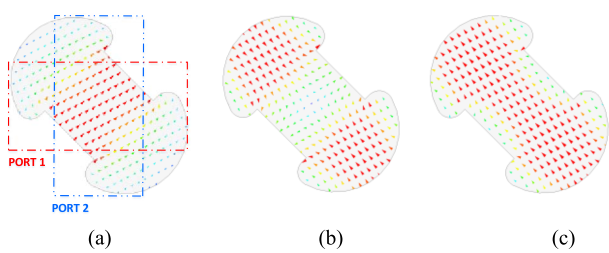

Fig. 2. Electrical field distribution of the modes inside the twist cavity. (a) Dominant mode: cut-off frequency 120 GHz. (b) Second mode: cut-off frequency 211 GHz. (c) Third mode: cut-off frequency 223 GHz.

this particular mode allows the rotation of the field from 0° to 90° at the opposite port. It should be noted that additional nondominant modes could propagate inside the twist cavity as well. These modes are of utmost importance for the twist performance, and overlooking them during the structure design would lead to incorrect results.

The electrical field distribution of the first, second, and third modes of the structure is illustrated in Fig. 2. These modes resemble TE_{10}, TE_{20}, and the antisymmetric TE_{10} modes in a rectangular waveguide. Thus, it is clear that the cut-off frequencies of those modes are intrinsically related with the equivalent "a" and "b" dimensions for a rectangular waveguide. It is essential to highlight that the second and third modes are evanescent for the input–output rectangular waveguides connected at ports 1 and 2, that is, they propagate only inside the twist cavity. In Fig. 3, the cut-off frequencies of the second and third modes are analyzed for the standalone twist structure. Moreover, the mode propagation was simulated for the twist connected to a rectangular waveguide in only one of its ports. When the first mode of the twist cavity is excited,

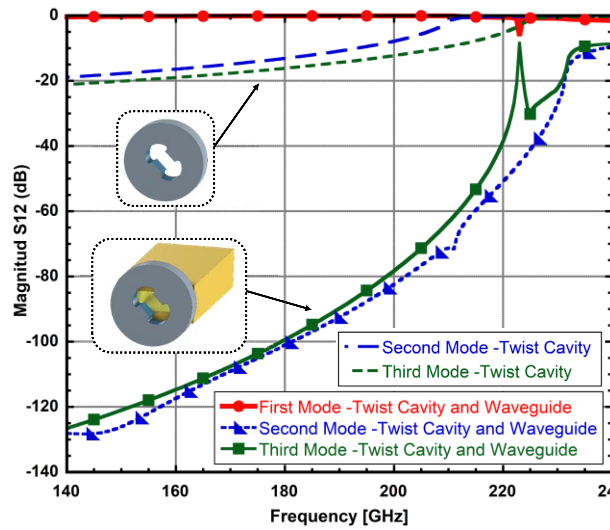

Fig. 3. Propagation of the second and third modes for the standalone twist cavity and the twist cavity connected to a rectangular waveguide. The third mode will introduce a resonance in the response.

the TE_{10} mode is observed at the output of the rectangular waveguide, which proves its role in the field rotation process. It is interesting to note that the third mode of the structure resonates at its cut-off frequency, that is, at 223 GHz. This limits the design bandwidth.

B. Twist Design

The waveguide twist was designed using the full-wave 3-D simulator Ansys high-frequency structure simulator (HFSS) aiming at the frequency range 140–220 GHz. As the starting point for the design, the twist is considered as a quarter-wave section of WR-5.1 waveguide with rounded walls. Therefore, the initial value for A was set to 648 μm, which corresponds to the "b" dimension of the standard waveguide. Meanwhile, B and R were selected to define the "a" dimension, that is, 1295 μm for our design. For simplicity, the dimension B was identical to A. Thus, the starting value for R was 347 μm. Increasing the radius of the half-circular apertures improves the matching of the design and its bandwidth. Nevertheless, the value of R will be limited by the appearance of a resonance in the upper part of the frequency band.

It is important to note that the radius of curvature $R2$ was introduced to ease the fabrication of the structure, and it does not affect the overall performance of the waveguide twist.

The final values were obtained through optimization in Ansys HFSS. Simulations of the optimized design showed a return loss better than 20 dB over the design band and 0.3-dB insertion loss.

C. Tolerance Analysis

In order to address the fabrication and misalignment tolerances of the design, two extreme scenarios were considered and presented in Fig. 4. For the first scenario, all the linear dimensions were increased simultaneously by 10 μm. Meanwhile, for the second scenario, the linear dimensions of the twist were decreased by 10 μm. Both simulations included

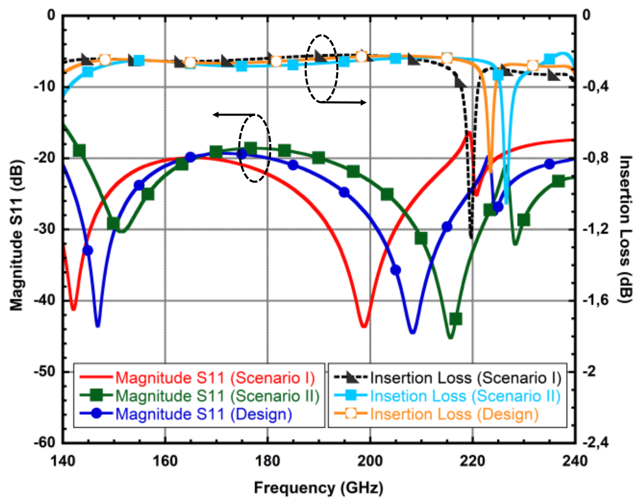

Fig. 4. Tolerance analysis of the waveguide twist. Two scenarios are simulated. Scenario 1: fabrication error of $+10$ μm in all the parameters. Scenario 2: fabrication error of -10 μm in all parameters. Both simulations introduce 20-μm misalignment and 2° error of angular positioning. The actual simulated design is plotted for reference.

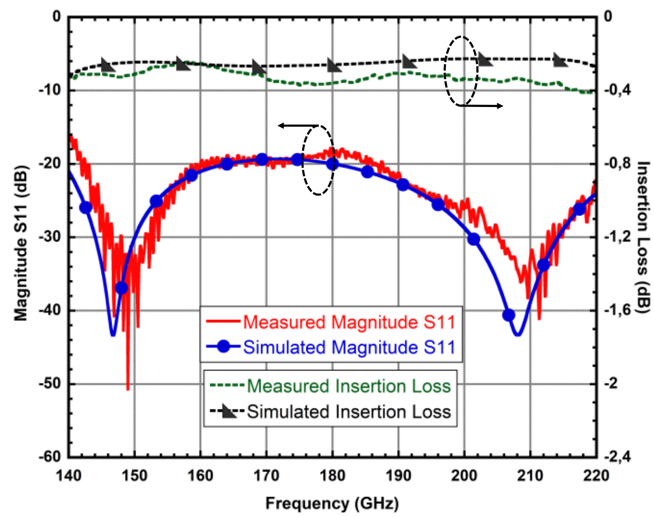

Fig. 5. Measured and simulated scattering parameters for the fabricated twist.

a 20-μm misalignment between the waveguide twist and the input and output ports. Also, to address tolerance to angular positioning, a 2° alignment error was included in both scenarios. From Fig. 4, it is clear that the operational bandwidth of the waveguide twist is limited by the presence of a resonance at the higher end of the band. The third mode of the structure was found to be responsible since its cut-off frequency coincided with the resonance appearance. Moreover, the analysis of both scenarios showed that the response would remain resonant free as far as the maximum deviation in each parameter remains below 10 μm. Furthermore, the design is tolerant to 20-μm misalignment and up to 2° error in angular positioning.

III. Results and Discussion

The twist fabricated of brass through direct milling is shown in Fig. 1(b).

The structure was characterized using the Keysight PNA-X 5242A with Virginia Diodes, Inc. (VDI) frequency extension modules WR-5.1. A standard thru-reflect-line (TRL) calibration was applied between 140 and 220 GHz. The measurement was performed employing a 90° continuous twist used in [16] placed at port 1 to level the VDI extension modules on the bench. This additional twist rotates 90° the polarization of the port, avoiding the need for physical rotation of the extension module itself during the twist measurements. This yields a more accurate result as the setup is not disturbed after calibration. The continuous twist response was deembedded from the S parameter data by postprocessing.

The simulated and measured performance of the fabricated twist is illustrated in Fig. 5. The return loss is above 20 dB over most of the band, whereas insertion losses are less than -0.4 dB. The experimental data were found in good agreement with simulation, as shown in Fig. 5.

Table I provides a comparison between the twist presented in this letter and other implementations found in the literature. Although designs as in [16] and [17] achieve excellent

TABLE I
Comparison of the State-of-the-Art Twists

Ref	Frequency [GHz]	Fractional Bandwidth	Total Length [λ_G]	Total Length [λ_0]	IL* [dB]	RL** [dB]
[16]	140-220	44%	1.8	2.4	0.2	30
[14]	220-320	37%	> 4	> 4	0.5	~20
	500-700	33%	-	-	2.5	20
[4]	75-110	37%	1.12	1.45	0.11	25
[13]	600-750	22%	0.43	0.56	0.5	20
[17]	220-330	40%	8.75	11.23	0.6	~25
This Work	**140-220**	**44%**	**0.3**	**0.39**	**0.4**	**~20**

*IL: Insertion Loss **RL: Reflection Loss
λ_G: guided wavelenght λ_0: Free Space Wavelength*

performance, its total length compromises its usefulness in highly integrated systems. From this comparison, it is clear that the twist presented in this letter stands out for its compactness, performance, and simplified manufacturing.

IV. Conclusion

A novel 90° single-step twist with simple and compact geometry has been presented. An analysis of the propagation modes inside the twists' cavities has been explored and a good agreement between the experimental data and simulations supports the proposed principle of operation. Experimental results have shown 44% fractional bandwidths with 20-dB return loss over most of the operational RF band. The design is limited by the appearance of the third mode inside the twist. However, it is possible to avoid in-band resonances through careful design of the structure. We have shown that our twist is well-suited for fabrication through standard milling techniques at least up to 220 GHz. Moreover, their simple and compact design makes them suitable and advantageous for a wide variety of applications from microwave to millimeter-wave range.

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