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Arbitrary-Angle Single-Step Waveguide Twist for Quasi-Octave Bandwidth Performance

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Abstract—Aquasi-octave bandwidth arbitrary-angle compact waveguide twist using a single matching step is presented. The proposed twist, based on a single intermediate ridge waveguide section that broadens its mono-mode operation, exhibits a similar wave impedance to the rectangular waveguide connected to its ports thus facilitating the reflections minimization in an extended frequency range. An exemplary 45° twist has been manufactured in the 10 GHz to 19.3 GHz frequency range ($\sim 64\%$) for demonstration purposes. The measured data are in concordance with those predicted by the simulation. This result represents, to the authors' knowledge, today's state-of-the-art in terms of compactness and bandwidth performance.

1. INTRODUCTION

Waveguide twists are key components in many communication systems in which low insertion losses, sharp defined bandwidths or high power management require fixed polarization rotation at any arbitrary angle using waveguide technology. There are different options to perform this function such as continuous rotation which is common in commercial solutions [1]. Although it can be set to a predetermined rotation angle with excellent electrical performance in terms of return loss, this solution is beyond the compactness concept, and it is not suitable for integrated systems. Moreover, the manufacture process may require dedicated techniques that could lead to expensive final products.

An approach to a more compact solution is the concatenation of a different number of quarter-wavelength-like sections with specific angular offset between them [2–6]. These works can be easily adjusted in order to get an arbitrary polarization rotation angle, but they rely on the number of sections to obtain a wide bandwidth with good return and insertion losses; therefore, they may also result in long solutions in terms of wavelength.

If maximum compactness is required, and different options that only need a single step section have been developed. These options, which present different lengths, but all of them are short in terms of wavelength, generally make use of a ridge section to always accomplish a 90° angle rotation [7–10]. Then these designs are optimized for orthogonal input-output polarizations and show good electrical results with a return loss in the range of 20–30 dB for limited fractional bandwidths of 30% or less. Better results can be obtained for rotation angles lower than 90° such as in [11], where a 45° twist obtains a return loss of 32 dB in a 38% bandwidth. In the same work, simulations without experimental validation show how a return loss better than 40 dB could be reached for a 40% relative bandwidth by using additional sections at one or both sides of the basic twist. Similar results are obtained experimentally in [12] where a configuration including two bow-tie sections is used to achieve full band (40%) performance.

All the previous works are not enough when dealing with some applications demanding very broad bandwidths such as radio astronomy, where the frequency range has a direct impact on the receiver sensitivity. In this work, a quasi-octave bandwidth (64%) and compact twist based on just one ridge

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section is presented. The twist internal shape, defined by two single parameters, named M and D and dependent on the twist angle, is designed to equalize the ridge and the rectangular waveguides wave impedances in a broad frequency range. Since the cutoff frequencies of the twist and rectangular waveguide are slightly different, the length of the twist has to be carefully controlled.

2. TWIST ELECTRICAL DESIGN

Twist geometry is shown in Fig. 1 together with the design parameters: ϕ, D, M and L, where L defines the ridge thickness. Input and output rectangular waveguides are also sketched for clearance, where the output waveguide is rotated an arbitrary angle ϕ with respect to the input waveguide. Points defining the twist and port waveguide coordinates are indicated in Fig. 1 while the equations for obtaining their values are presented in Table 1. Equations for points 17 to 22 are obtained from symmetry properties. From Fig. 1 and Table 1 it is clear that, for a given angle, only three parameters are required to design the twist completely. Apart from these key parameters, rectangular waveguide dimensions A and B are needed. Since we are aiming for a quasi-octave bandwidth performance, the natural relationship $A = 2B$ should not be fulfilled. Instead, dimension B must be slightly lower, $B \sim 0.47A$, which widens the internal mono-mode behavior in the structure and enables to approach an octave bandwidth from a practical point of view.

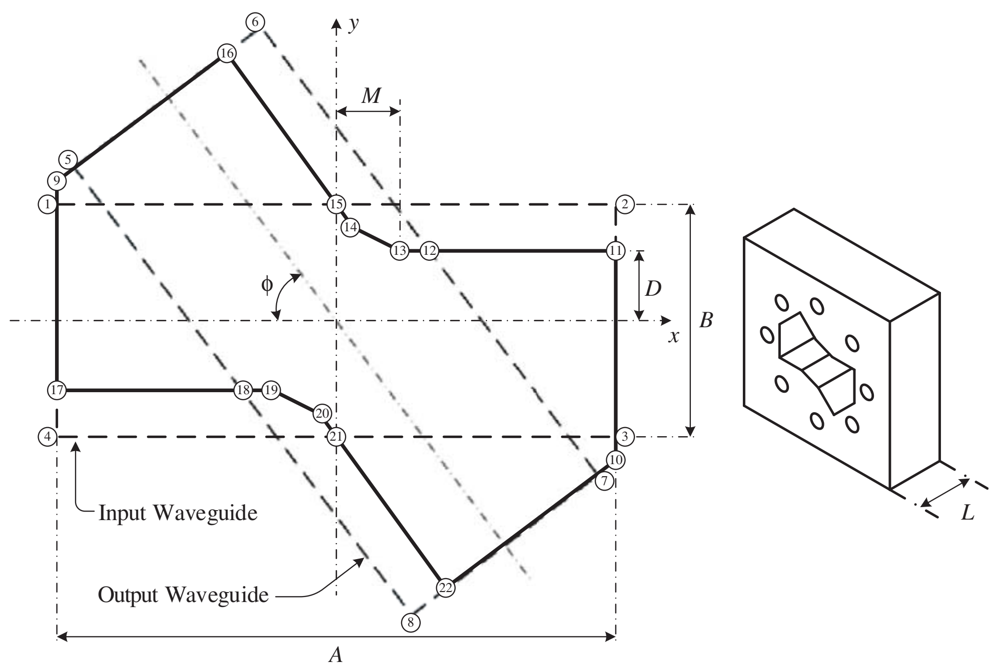

Figure 1. Waveguide twist internal shape (solid line) with the definition of the design parameters (ϕ, D, M, L). Rectangular waveguides ($A \times B$) connected to input and output ports are also shown for reference (dashed lines). Every single point defining the proposed geometry is indicated using a number.

The almost unique attempt to rigorously analyze the matching behavior of a rotated single ridge twist topology located between two rectangular waveguides was done by Asao et al. [7]. They considered a coherent electrical equivalent circuit that explains in a clear way the inherent bandwidth limitations due to the internal impedance transformation of the two shunt reactances related to the waveguide conversion. To overcome these constraints, this work proposes a preliminary and broadband wave impedance equalization of the two guiding geometries, ridged and rectangular, by adjusting the design parameters M and D shown in Fig. 1 for a given rotation angle ϕ. As an example, Fig. 2 shows such preliminary impedance equalization for a standard $\phi = 45°$ twist. As predicted by the circuit theory, the intrinsic impedance differences close to cutoff, which directly affects the desired broadband shunt

Table 1. Twist geometry points definition.

Number	Coordinate x	Coordinate y
1	$-A/2$	$B/2$
2	$A/2$	$B/2$
3	$A/2$	$-B/2$
4	$-A/2$	$-B/2$
5	$-A/2 \cdot \cos(\phi) - B/2 \cdot \sin(\phi)$	$A/2 \cdot \cos(\phi) - B/2 \cdot \sin(\phi)$
6	$-A/2 \cdot \cos(\phi) + B/2 \cdot \sin(\phi)$	$A/2 \cdot \cos(\phi) + B/2 \cdot \sin(\phi)$
7	$A/2 \cdot \cos(\phi) + B/2 \cdot \sin(\phi)$	$-A/2 \cdot \cos(\phi) + B/2 \cdot \sin(\phi)$
8	$A/2 \cdot \cos(\phi) - B/2 \cdot \sin(\phi)$	$-A/2 \cdot \cos(\phi) - B/2 \cdot \sin(\phi)$
9	$-A/2$	$A/2 \cdot \tan(\phi/2)$
10	$A/2$	$-A/2 \cdot \tan(\phi/2)$
11	$A/2$	D
12	$(B/2)/\sin(\phi) - D/\tan(\phi)$	D
13	M	D
14	$\mathrm{sqrt}(M^2 + D^2)$ $\cdot \cos(180 - \phi - a\tan(D/M))$	$\mathrm{sqrt}(M^2 + D^2)$ $\cdot \sin(180 - \phi - a\tan(D/M))$
15	$\mathrm{sqrt}(((B/2)/\sin(\phi) - D/\tan(\phi))^2 + D^2)$ $\cdot \cos(180 - \phi - a\tan(D/((B/2)/\sin(\phi) - D/\tan(\phi)))$	$B/2$
16	$-A/2 \cdot \cos(\phi) + D \cdot \sin(\phi)$	$A/2 \cdot \cos(\phi) + D \cdot \sin(\phi)$

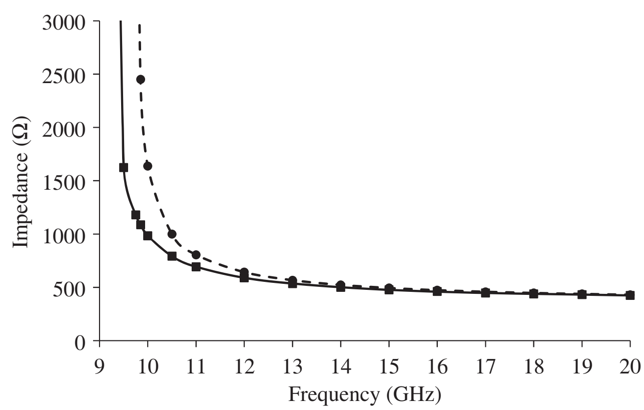

Figure 2. Calculated waveguide impedance across the band for a 45° twist section (solid line with squares) and the rectangular waveguide connected to its ports (dashed line with dots).

reactance transformation, can be easily absorbed by a careful selection of the ridge length L for a specific rotation angle ϕ.

The design starts defining the frequency band of interest, being from 10 GHz to 19.3 GHz ($\sim 64\%$) in the subsequent calculations. The dimension A is chosen in such a way that the TE_{10} mode cutoff frequency is close to the lower end of the design band. On the other hand, the highest operative frequency is limited by the appearance of the first higher order mode in the structure. Initial values for design parameters are set as follows: $L = 0.5\lambda_0$, $D = 0.25B$ and $M = 0.25A$, where λ_0 is the free space wavelength close to the geometric center frequency. From this starting point, an iterative optimization process was done by using a Mode Matching simulation tool like μWave Wizard from Mician GmbH. A few simulations were carried out for obtaining appropriate parameter values as a function of the twist angle so that the matching response systematically exhibits a four pole behavior. These optimum values, normalized to λ_0, are presented in Table 2. Obviously, the twist performance in terms of VSWR

Table 2. Parameter values for the proposed twist. Values normalized to λ_0.

ϕ	A	B	L	M	D
10°	0.744	0.353	0.357	0.119	0.165
15°	0.744	0.353	0.410	0.111	0.161
20°	0.744	0.353	0.431	0.105	0.158
25°	0.744	0.353	0.446	0.106	0.154
30°	0.744	0.353	0.462	0.111	0.149
35°	0.744	0.353	0.474	0.121	0.144
40°	0.744	0.353	0.483	0.129	0.138
45°	0.744	0.353	0.493	0.135	0.133
50°	0.744	0.353	0.493	0.142	0.126
55°	0.744	0.353	0.507	0.142	0.123
60°	0.744	0.353	0.507	0.148	0.117
65°	0.744	0.353	0.511	0.151	0.113
70°	0.744	0.353	0.513	0.150	0.109
75°	0.744	0.353	0.512	0.152	0.104
80°	0.744	0.353	0.511	0.153	0.099
85°	0.744	0.353	0.508	0.150	0.096
90°	0.744	0.353	0.504	0.147	0.092

is degraded as the twist angle increases, but excellent values better than −30 dB for a worst-case 90° twist can be obtained in the whole frequency range by maintaining the four pole response as shown in Fig. 3. For the sake of clarity, Fig. 4 presents the simulated reflection values for the most typical twist angles, which are $\phi = 45°$ and $\phi = 90°$, so a straightforward comparison can be established with alternative structures found in the literature.

In order to demonstrate the real performance of such structures, a 45° twist was designed to cover a 64% bandwidth. This particular twist is very useful in antenna feeding networks for different applications when orthogonal waveguide orientations need to be parallelized. In particular, this 45° twist

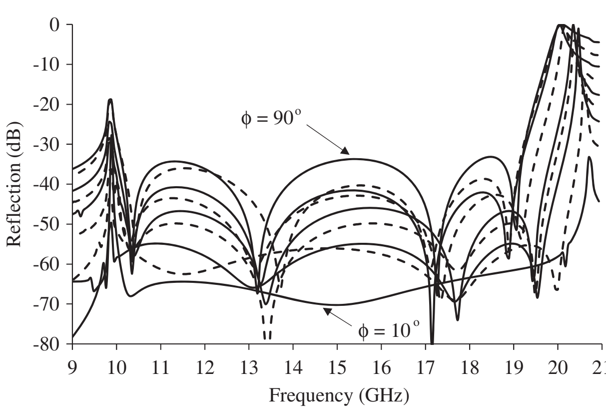

Figure 3. Simulated reflection of the proposed twist design for different values of the twist angle, which varies from $\phi = 10°$ (bottom curve) to $\phi = 90°$ (top curve) in 10° steps. Solid and dashed lines are used alternatively for clearance.

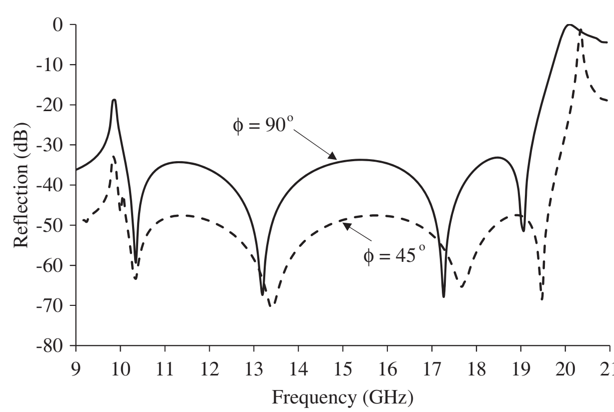

Figure 4. Simulated reflection of the proposed twist design for the most typical twist angles, $\phi = 45°$ (dashed line) and $\phi = 90°$ (solid line).

is intended to be connected or included at the turnstile-based orthomode transducer (OMT) rectangular output ports of a radio astronomy receiver, since this kind of OMTs have an internal structure which results in orthogonally-oriented ports. This facilitates the allocation of multiple receivers in reduced environments. Moreover, due to the minimum number of sections of the proposed structure this twist can be implemented in platelet OMTs adding just one layer, thus improving the compactness of traditional solutions [13].

3. MANUFACTURE AND MEASURED RESULTS

The waveguide twist described in the previous section was fabricated in aluminum, Fig. 5, using a standard CNC milling process. This implies that the internal corners have been rounded with a radius of 1 mm for this particular case. Concerning the measurement procedure, a couple of dedicated in-line coaxial-to-waveguide transitions, made of a four-step centered ridge section [14], were designed and fabricated to assure an octave bandwidth operation. These transitions, manufactured in aluminum and assembled with commercial SMA connectors, have been included in Fig. 5. This overcomes the use of several standard coaxial-to-waveguide transitions as well as dedicated tapered sections in the measurement process. Furthermore, two delay lines, also shown in Fig. 5 and having different lengths, have been designed to act as $\lambda_g/4$ standards during the Thru-Reflect-Line (TRL) calibration process. Due to the large bandwidth, the TRL frequency range was divided into two sub-bands where each band required a different $\lambda_g/4$ delay standard, with λ_g being the waveguide wavelength at the center frequency in the corresponding sub-band. With this strategy, the measurement system is calibrated once at the rectangular waveguide ports plane, and the twist performance is measured in the whole bandwidth in just one test run of the VNA.

Figure 5. Picture of the fabricated twist along with coaxial-to-waveguide transitions and delay lines acting as $\lambda_g/4$ standards for the TRL calibration.

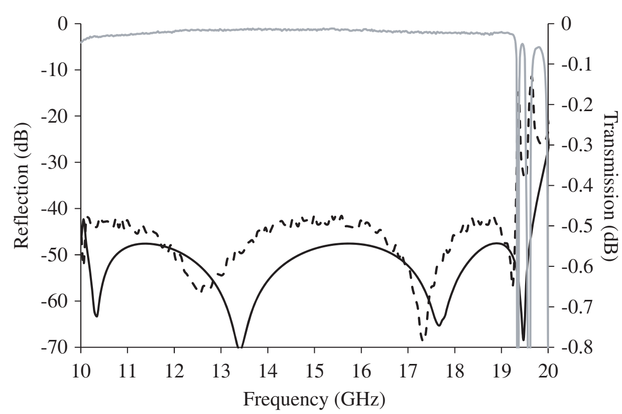

Figure 6. Comparison between measured and simulated performances for the designed 45° twist: Simulated reflection (black solid line), measured reflection (black dashed line) and measured transmission (grey solid line).

As can be appreciated in Fig. 6, where measured and simulated results are plotted together for comparison purposes, the experimental return loss is better than 40 dB in the band of interest 10–19.3 GHz, thus approaching the predicted behavior. The measured insertion loss is around 0.04 dB, which is below the measurement uncertainty. Simulated insertion loss is not included due to its ideal response with a nearly flat behavior and negligible values in the whole band. Regarding the power handling capabilities, although we do not have access to high-power phenomena simulators, such as corona or multipactor effects, conservative theoretical simulations show that this structure can manage several kW.

As a summary of published data, Table 3 presents a comparison between the measured results in this work and other results found in the literature, so the advantages of the proposed structure can be clearly appreciated.

Table 3. Results comparison between published twist waveguide structures. Lengths are normalized to λ_g, being λ_g the rectangular waveguide wavelength at center frequency of the stated bandwidth.

Reference	Twist angle (°)	Bandwidth (GHz)	Return Loss (dB)	Number sections	Length (λ_g)
[2]	90	38% (75–110)	25	4	0.62
[4]	90	37% (10–14.5)	25	4	0.9
[5]	90	49% (20–33)	20	4	1.71
[6]	45	42% (26–40)	25	2	0.56
[7]	90	22% (13.25–16.5)	30	1	0.22
[8]	90	32% (10.5–14.5)	30	1	0.2
[9]	90	16% (17.5–20.6)	35	1	0.2
[10]	90	22% (600–750)	20	1	0.49
[11]	45	40% (22.5–34)	30	2	0.33
[12]	90	40% (10–15)	40 30	2 1	0.28 0.18
This work (measured)	45	64% (10–19.3)	41	1	0.35
This work (simulated)	90	64% (10–19.3)	33	1	0.36

4. CONCLUSION

The procedure to design an arbitrary-angle waveguide twist with excellent performances, which covers an octave bandwidth, has been presented. The twist comprises a single and compact ridge section simply defined by three physical parameters. The evolution of these parameters with the rotation angle has a smooth behavior, and it is also provided for easing the design process. For demonstration purposes, a 45° twist has been manufactured covering the 10–19.3 GHz frequency range (64% fractional bandwidth). The measured return loss is better than 41 dB with an almost negligible insertion loss level. To the authors' knowledge, the proposed structure represents the current state-of-the-art in terms of compactness, bandwidth and angle flexibility combined characteristics.

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