COMPUTER-AIDED DESIGN OF MACHINABLE RECTANGULAR WAVEGUIDE TWISTS

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ABSTRACT

The computer-aided design of new machinable rectangular waveguide twists for integrated waveguide technology is introduced. The novel 90 degree twist components require only purely rectangular waveguide sections. This allows fabrication by modern CNC machines and, at the same time, simplifies computer-aided design procedures since the eigenfunctions of all individual sections involved are well determined. Three different design guidelines are presented for operation at the lower end, the medium range and the upper end of a waveguide band. The guides connected to the actual twist section can be of different cross-section which might eliminate the need for additional impedance transformers. The 90-degree twist component is extremely short and, therefore, ideally suited for application in satellite communication systems. Finally, a 270-degree twist component is discussed with respect to bandwidth enlargement.

Keywords: Waveguide Twist, Integrated Waveguide Technology, Mode Matching, Computer-Aided Design.

1. INTRODUCTION

Twists in rectangular waveguides can be realized either from straight guides for a prescribed degree of rotation or as twisted waveguide components, where several slices of rectangular waveguides are individually rotated on a common axis. Theories on the propagation characteristics of continuously twisted rectangular waveguides have been published in the early eighties (Refs. 1-4), and twisted waveguide components have been investigated since the fifties for applications as filters and field rotators (Refs. 5, 6).

However, modern integrated waveguide technology places two restrictions on the realization of twisted waveguide sections. The components must be, first, designed and fabricated without post-assembly tuning possibilities and, secondly and more important, machinable by CNC machines. Only one structure addressing these problems has been proposed so far. It involves a continuously varying L-shaped guide for 90-degree rotation (Ref. 7). The design is not only several wavelengths long but is also inconvenient for computer-aided design strategies since it involves L-shaped waveguide cross-sections.

Therefore, this paper presents short and machinable rectangular waveguide twists which are formed exclusively by rectangular cross-sections (Fig. 1) and, therefore, can be efficiently analyzed by mode-matching techniques. The mode of operation is based on cascading a number of rectangular waveguide sections where each discontinuity contributes to a conversion from the TE_{10} to the TE_{01} mode, the latter of which is the fundamental mode of the output guide in a 90-degree rotation. The advantage of this design is that the overall length is less than three sixteenths of a wavelength for a 90-degree twist. Due to its compactness, the bandwidth of this structure is limited to about three to five percent for 20 dB input return loss. This is sufficient for many applications. For a more broadband design, three 90-degree components are cascaded to form a 270-degree twist section. By this measure, the bandwidth can be increased to up to twelve percent. The additional space requirements compared to a single 90-degree section are not extensive so that the component's overall length lies between 0.4 and 1.3 guide wavelengths at midband frequency.

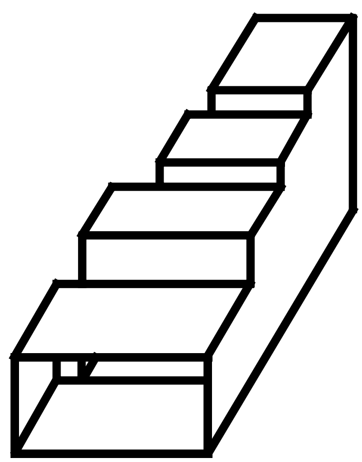

Figure 1: *Machinable 90-degree rectangular waveguide twist.*

2. THEORY

2.1 Analysis

The analysis procedure is based on a rigorous full-wave mode-matching technique (e.g. Ref. 8). Intermediate regions are introduced in the model to calculate cross-section overlapping discontinuities, i.e., where the smaller waveguide's cross-section is not a subset of that of the larger one's (Fig. 2).

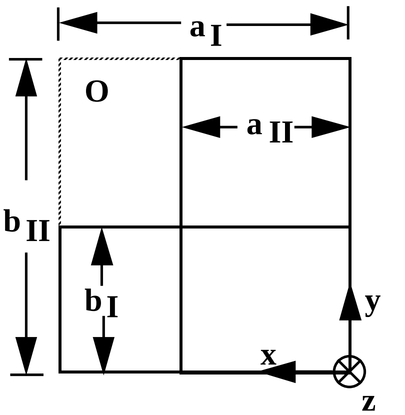

Figure 2: *Discontinuity formed by two individual waveguides in Fig. 1. Dashed frame denotes cross-section of intermediate region.*

The electromagnetic field in region *i=I, O, II*

$$\vec{E}^i = \frac{1}{j\omega\varepsilon_0}\nabla\times\nabla\times(A^i_{ez}\vec{e}_z) + \nabla\times(A^i_{hz}\vec{e}_z) \qquad (1)$$

.

$$\vec{H}^i = \frac{-1}{j\omega\mu_0}\nabla\times\nabla\times(A^i_{hz}\vec{e}_z) + \nabla\times(A^i_{ez}\vec{e}_z) \qquad (2)$$

is derived from vector potential components

$$A^i_{hz} = \sum_{m=0}^{M-1}\sum_{n=0}^{N-1}\sqrt{Z^i_{hmn}}\,T^i_{hmn}(x,y) \bullet \left[F^i_{hmn}\exp(-jk^i_{zhmn}z) + B^i_{hmn}\exp(jk^i_{zhmn}z)\right] \qquad (3)$$

$$A^i_{ez} = \sum_{m=1}^{M-1}\sum_{n=1}^{N-1}\sqrt{Y^i_{emn}}\,T^i_{emn}(x,y) \bullet \left[F^i_{emn}\exp(-jk^i_{zemn}z) - B^i_{emn}\exp(jk^i_{zemn}z)\right] \qquad (4)$$

where $F_{h,e}$ and $B_{h,e}$ are amplitudes of waves traveling in positive and negative z-direction, respectively. Immittances and phase constants are given by

$$Z^i_{hmn} = \frac{\omega\mu_0}{k^i_{zhmn}} \qquad Y^i_{emn} = \frac{\omega\varepsilon_0}{k^i_{zemn}} \qquad (5)$$

$$k^i_{zh,\,emn} = \sqrt{\omega^2\mu_0\varepsilon_0 - \left(\frac{m\pi}{a_i}\right)^2 - \left(\frac{n\pi}{b_i}\right)^2} \qquad (6)$$

and the cross-section functions are those of empty waveguides

$$T^i_{hmn}(x,y) = A^i_{mn}\frac{\cos\left(\frac{m\pi}{a_i}x\right)}{\sqrt{1+\delta_{0m}}}\,\frac{\cos\left(\frac{n\pi}{b_i}y\right)}{\sqrt{1+\delta_{0n}}} \qquad (7)$$

$$T^i_{emn}(x,y) = D^i_{mn}\sin\left(\frac{m\pi}{a_i}x\right)\sin\left(\frac{n\pi}{b_i}y\right) \qquad (8)$$

where δ_{0k} denotes the Kronecker delta. Once the generalized scattering matrix of the discontinuity of Fig. 2 is obtained using a vanishing length for the intermediate region, a certain length of waveguide *II* is added. This forms the basic block for the analysis. An entire twist component is analyzed by cascading individual blocks. Between 25 and 35 TE_{mn} modes plus their respective TM_{mn} parts are sufficient for convergence within 1 dB of input return loss. The analysis of a two-section 90-degree twist as shown in Fig. 1 requires approximately 10 minutes of CPU time on a 66 MHz personal computer.

2.2 Design

Through numerous tests and optimization (e.g., Ref. 9), it has been found that a two-section design is sufficient and that optimization of section lengths and an increase inthe number of sections does not significantly improve the performance of a 90-degree twist. Therefore, design guidelines have been developed for application in the lower, medium and upper range of a waveguide band. Let a_I, b_I and a_{II}, b_{II} be the cross-sections of the input and output waveguides, respectively, and let K be the number of sections between input and output. Then the waveguide cross-section dimensions a_k, b_k of section k are given as

$$a_k = \frac{a_I + a_{II}}{2} + R\cos\left(\phi_o + \frac{\pi k}{K+1}\right) \qquad (9)$$

$$b_k = \frac{b_{II} + b_I}{2} + R\sin\left(\phi_o + \frac{\pi k}{K+1}\right) \qquad (10)$$

with

$$R = \frac{1}{2}\sqrt{(a_I - a_{II})^2 + (b_{II} - b_I)^2} \qquad (11)$$

$$\phi_o = -\arctan\frac{b_{II} - b_I}{a_I - a_{II}} \qquad (12)$$

for application at the lower end of a waveguide band,

$$a_k = a_{II} + (a_I - a_{II}) \cos\left(\frac{0.5\pi k}{K+1}\right) \qquad (13)$$

$$b_k = b_I + (b_{II} - b_I) \sin\left(\frac{0.5\pi k}{K+1}\right) \qquad (14)$$

for applications in the medium range, and

$$a_k = a_I - \frac{k}{K+1}(a_I - a_{II}) \qquad (15)$$

$$b_k = b_I + \frac{k}{K+1}(b_{II} - b_I) \qquad (16)$$

at the upper waveguide band end. The section lengths L_k should be chosen close to

$$L_k = \begin{cases} 3\lambda_{gk}/(16K) & \text{Equs.9-12} \\ \lambda_{gk}/(16K) & \text{Equs.13-16} \end{cases} \qquad (17)$$

where λ_{gk} is the guide wavelength of the lowest propagating mode in section k. These guidelines produce 90-degree twists with 20 dB return-loss bandwidths between six (lower band end) and two (upper band end) percent.

3. RESULTS

Fig. 3 displays the typical performances of the three different design variants operating in the lower, medium and upper region of the Ku-band. The 20dB-return-loss bandwidths are 5.8, 3.3 and 3.0 percent, or 740, 500 and 530 MHz, respectively.

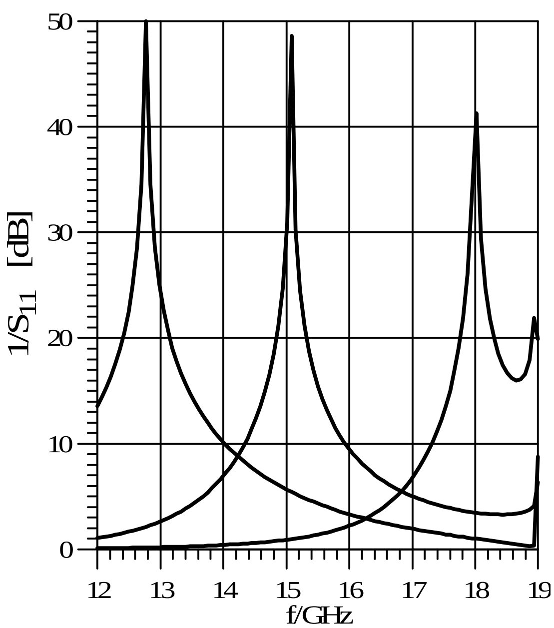

Figure 3: *Typical return loss behavior of two-section twist designs according to Eqs. 9-17.*

At the example of a WR75 (10 - 15 GHz) and a Ku-band (12.4 - 18 GHz) waveguide, Fig.4 demonstrates that a 90° twist and a change in waveguide dimensions can be obtained simultaneously and, therefore, can eliminate the need for additional impedance transformers. This two-section component is designed according to Equs. 9 - 12 for WR75 as input and Ku-band as output waveguide. It achieves a 20dB-return-loss bandwidth of 3.6 percent, or 460 MHz. Note that this design does not produce a return-loss pole as those of Fig. 3. This is due to the different input and output dimensions which cause the return-loss peak to decrease as the difference in input/output cross-sections increases.

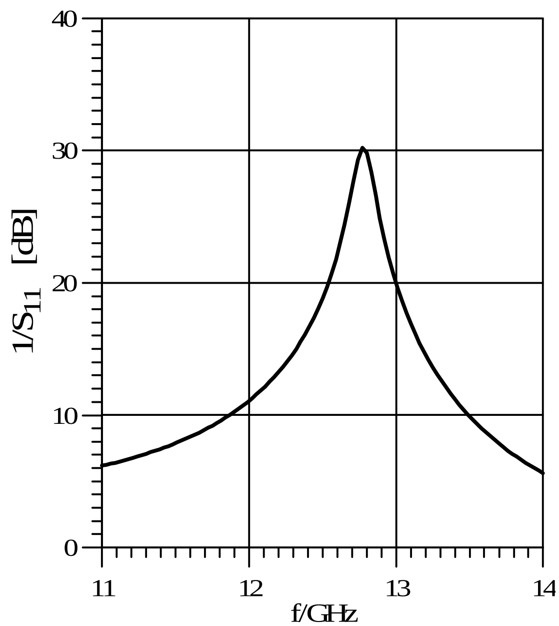

Figure 4: *Performance of a 90-degree rotation connecting a WR75 (input) and a WR62 (output) waveguide.*

The operation of the stepped waveguide twist (Fig. 1) is based on mode conversion from TE_{10} to TE_{01}. Since the amount of discontinuity to produce mode conversion decreases with an increasing number of steps between input and output guide, an increase in sections will not enlarge the bandwidth of the twist as has been observed in an attempt to increase the bandwidth by optimization, i.e., Ref. 9. The only possibility for bandwidth enlargement is to cascade individual 90-degree twist components. This is demonstrated in Fig. 5 at a WR75 waveguide example. Three 90-degree twist sections are designed separately with waveguide runs between them optimized in length. The return loss shows a three-pole performance - due to the three twist sections involved - and achieves a bandwidth of 1.1 GHz or 9.0 percent. Note that due to the compactness of the individual 90-degree twists, the length of the 270-degree component is only 1.25 guide wavelengths at midband frequency.

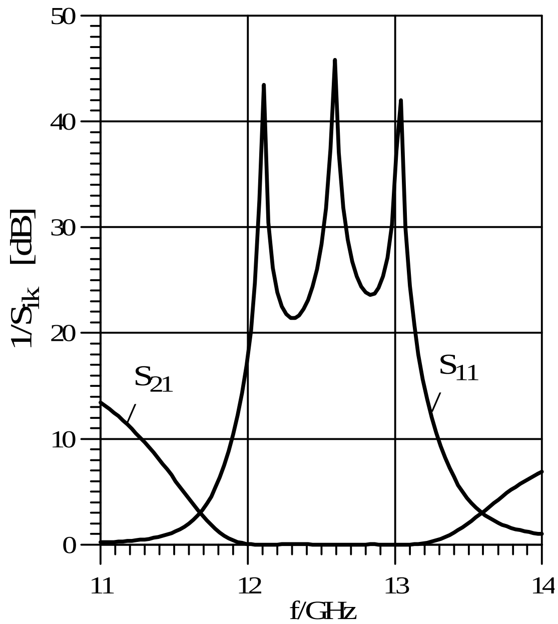

Figure 5: *Bandwidth enlargement by cascading three 90-degree twists to form a 270-degree rotation.*

4. CONCLUSIONS

A computer-aided design for machinable twists in integrated waveguide technology is introduced. Three different design variants for operation in the lower, medium and upper waveguide band are presented. The 90-degree twist components are extremely short and, as an additional option, are capable of joining waveguides of different cross-sections. The maximum bandwidth obtainable with a single 90-degree twist is approximately six percent. Bandwidth enlargement is possible by forming 270-degree twist components. Due to the fact that only waveguides of rectangular cross-sections are used, the mode-matching procedure to evaluate the overall performance is efficient and, therefore, operational on modern personal computers.

5. REFERENCES

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