# SHORT AND MACHINABLE 90° TWISTS FOR INTEGRATED WAVEGUIDE APPLICATIONS

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## ABSTRACT

New designs of $90^0$ twists for integrated rectangular waveguide applications are introduced. Three different design variants are presented which comprise several advantages compared to discrete twisted waveguides. First, the designs are machinable as required for integrated waveguide technology. Secondly, they are extremely short (one sixteenth of a wavelength) and, therefore, ideally suited for application in satellite communication waveguide bands. Thirdly, the guides connected to the actual twist section can be of different cross-section which reduces the need for additional impedance transformers. And finally, only rectangular instead of L-shaped cross-sections are utilized. Hence CAD procedures are simplified significantly, and the software is operational on personal computers.

The theoretical model used is verified by measurements at the fundamental step discontinuity formed by two double-plane offset-connected waveguides.

## I. INTRODUCTION

Rectangular waveguide twists are required in all kinds of waveguiding networks to connect and align individual components or subsystems. Experimental investigations on step-twist components have been carried out some decades ago [1, 2]. Subsequent studies focused on the propagation characteristics of twisted rectangular guides [3-6]. Discrete twist components are now readily available.

However, with the advent of integrated waveguide technology, where $90^0$ twists need to be fabricated from aluminum blocks, machinability has become a critical issue. This has been addressed in [7], where a continuous but varying L-shaped section is proposed which connects a rectangular waveguide to one rotated by $90^0$. Although this approach provides a 20dB-return-loss bandwidth over approximately 50 percent of the waveguide Q-band, the design is rather long (in extend of five wavelengths), which makes an application at lower frequencies (e.g., X-band) somewhat problematic. Moreover, this structure is difficult to handle with respect to computer-aided design purposes since the eigenmode spectra of several L-shaped waveguides must be evaluated by a lengthy numerical procedure.

Therefore, this paper presents a novel design of a $90^0$ waveguide twist for integrated waveguide applications (Fig. 1). The key features are: First, the component is extremely short which makes it suitable for frequencies around and below 10 GHz and, secondly, it comprises purely rectangular waveguide sections which allows machinability and, at the same time, significantly simplifies the numerical analysis procedure.

## II. THEORY

The design of the machinable $90^0$ waveguide twist is based on the mode-matching technique, e.g. [8]. The basic-block discontinuity involved is depicted in Fig. 2. An intermediate region of vanishing length, whose cross-section contains those of the two connected waveguides as subsets, is theoretically introduced in order to solve for the generalized scattering matrix of this junction. Since the structure is completely unsymmetric, the cross-section functions of TE and TM modes in the two waveguides i=I, II are given by

$$T_h^i(x,y) = \sum_{m=0}^{M-1}\sum_{n=0}^{N-1} A_{mn}^i \frac{\cos\left[\frac{m\pi}{a_i}(x-x_{oi})\right]}{\sqrt{1+\delta_{0m}}} \frac{\cos\left[\frac{n\pi}{b_i}(y-y_{oi})\right]}{\sqrt{1+\delta_{0n}}} \qquad (1)$$

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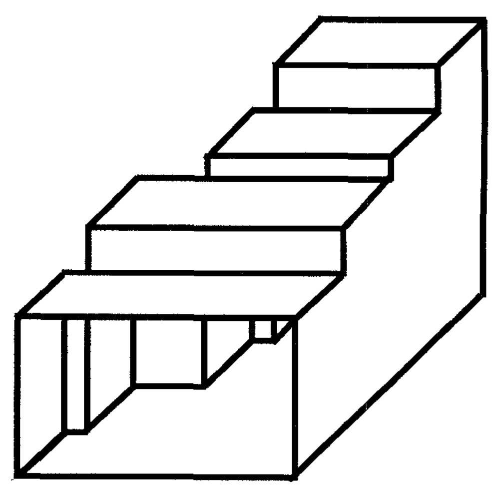

**Fig. 1** Machinable $90^0$ twist for integrated waveguide applications.

$$T_e^i(x,y) = \sum_{m=1}^{M-1}\sum_{n=1}^{N-1} D_{mn}^i \sin\left[\frac{m\pi}{a_i}(x-x_{oi})\right] \sin\left[\frac{n\pi}{b_i}(y-y_{oi})\right] \quad (2)$$

where $x_{oI} = y_{oI} = 0$, and $x_{oII} = x_o$, $y_{oII} = y_o$ can be positive or negative (Fig. 2).

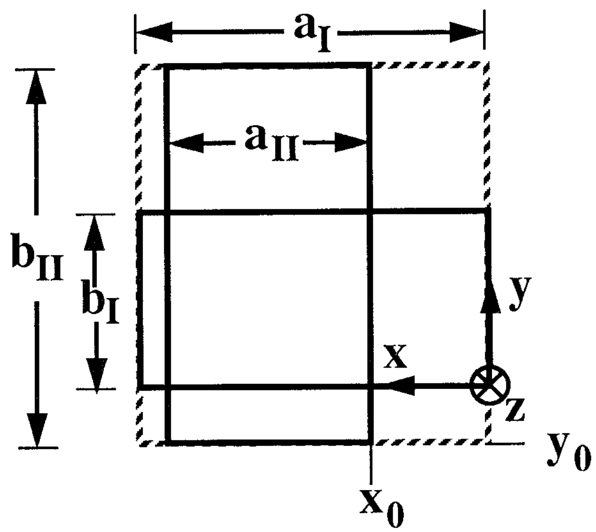


**Fig. 2** Discontinuity formed by offset-connected waveguides. Dashed frame denotes cross-section of intermediate region.

The operating principle of the stepped waveguide twist (Fig. 1) is primarily based on the conversion from the $TE_{10}$ mode of the incoming waveguide to the $TE_{01}$ mode, the fundamental mode of the output guide. It is obvious that for any of the different section profiles investigated (Fig. 3), the amount of discontinuity to excite the $TE_{01}$ mode decreases with an increasing number of steps along the profile. This is the reason why an increase in steps between input and output guide fails to enlarge the bandwidth of the twist as has been demonstrated by many optimization attempts using different strategies, e.g. [9]. All optimization routines tested reduce the lengths of the individual sections in such a way that the overall length of the twist equals approximately one sixteenth of the midband guide wavelength.

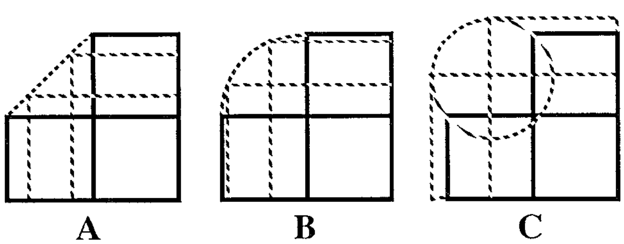


**Fig. 3** Design variants of twist-section profile.

Therefore, the following design formulas for the individual sections have been developed. Let $K$ be the number of sections between input and output waveguide, then the section lengths are given by

$$L_k = \lambda_{gk}/(16K) \quad (3)$$

where $\lambda_{gk}$ is the guide wavelength of the lowest propagating mode in section $k$. The fact that at least one mode needs to be above cutoff leads to the different twist profiles A, B, C (Fig.3) for applications in the upper, medium or lower frequency range, respectively, of a waveguide band. The different section profiles between input ($a_I x b_I$) and output ($a_{II} x b_{II}$) are given by:

Design A:

$$a_k = a_I - \frac{k}{K+1}(a_I - a_{II}) \quad (4)$$

$$b_k = b_I + \frac{k}{K+1}(b_{II} - b_I) \quad (5)$$

Design B:

$$a_k = a_{II} + (a_I - a_{II})\cos\left(\frac{0.5\pi k}{K+1}\right) \quad (6)$$

$$b_k = b_I + (b_{II} - b_I)\sin\left(\frac{0.5\pi k}{K+1}\right) \quad (7)$$

Design C:

$$a_k = \frac{a_I + a_{II}}{2} + R\cos\left(\phi_o + \frac{\pi k}{K+1}\right) \quad (8)$$

$$b_k = \frac{b_{II} + b_I}{2} + R\sin\left(\phi_o + \frac{\pi k}{K+1}\right) \quad (9)$$

where

$$R = \frac{1}{2}\sqrt{(a_I - a_{II})^2 + (b_{II} - b_I)^2} \quad (10)$$

$$\phi_o = -\arctan\frac{b_{II} - b_I}{a_I - a_{II}} \quad (11)$$

and the lengths obtained from (3) should be tripled for design C.

These guidelines produce $90^o$ twists of up to six percent bandwidth (20 dB return loss). The CPU time of a subsequent analysis is ten minutes on 66 MHz 486 PC.

## III. RESULTS

In order to validate the theoretical model for the basic step discontinuity shown in Fig. 2, a junction formed by two double-plane offset-connected Ku-band waveguides has been measured. Figs. 4 demonstrate good agreement between theory and experiment. The measured ripple between 13 and 14 GHz is caused by the extremely low-level transmitted signal to be detected. It is asumed that averaging in the measurement process would reduce this influence.

Fig. 5 displays the typical performances of the three different design variants of Fig. 3. The 20dB-return-loss bandwidths are 6.0, 3.0 and 2.7 percent for designs C, B and A, respectively. An increase in the number of sections between input and output waveguide will not result in a further increase in bandwidth as explained in the theory section. Consequently,

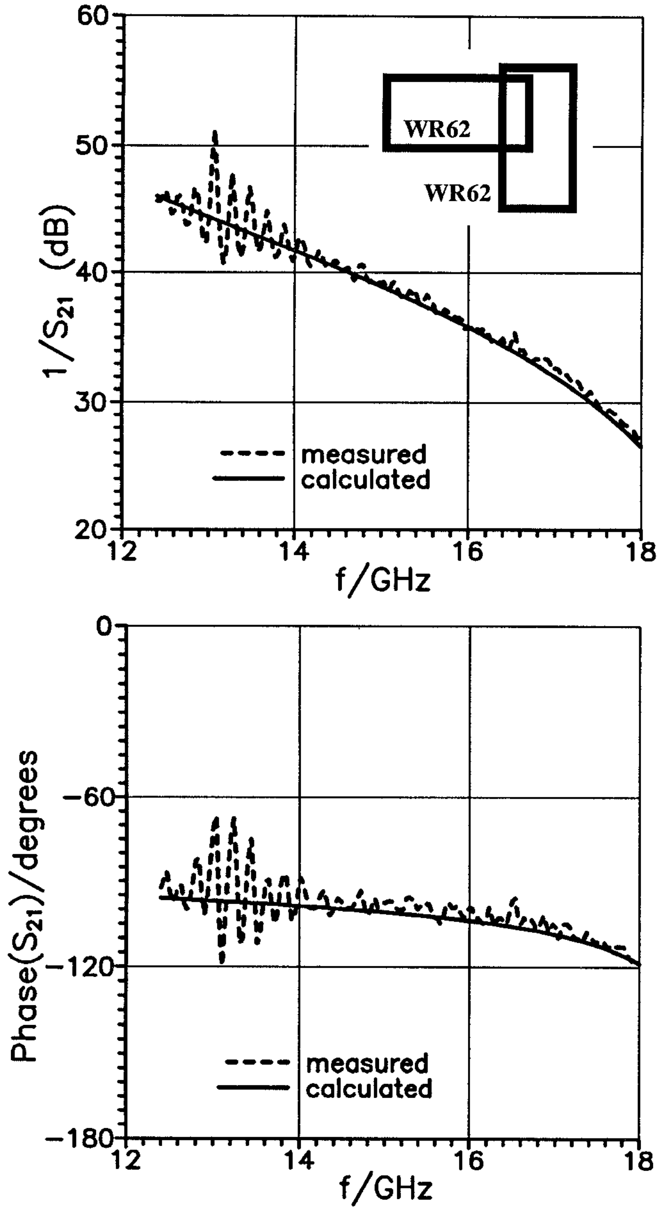


**Fig. 4** Comparison between theory and measurement at the example of a waveguide transition according to Fig. 2 in Ku-band; insertion loss (top), transmission phase (bottom).

the optimization of a five-section 90° twist - initially designed for variant B - could enlarge the 20dB-return-loss bandwidth only from 2.9 to 3.8 percent.

At the example of an X-band (8.2 - 12.4 GHz) and WR75 (10 - 15 GHz) waveguide, Fig.6 shows that a 90° twist and a change in waveguide dimensions can be obtained at the same time. The two-section design corresponds to variant B and achieves a 20dB-return-loss bandwidth of 3.4 percent centered around 11.5 GHz.

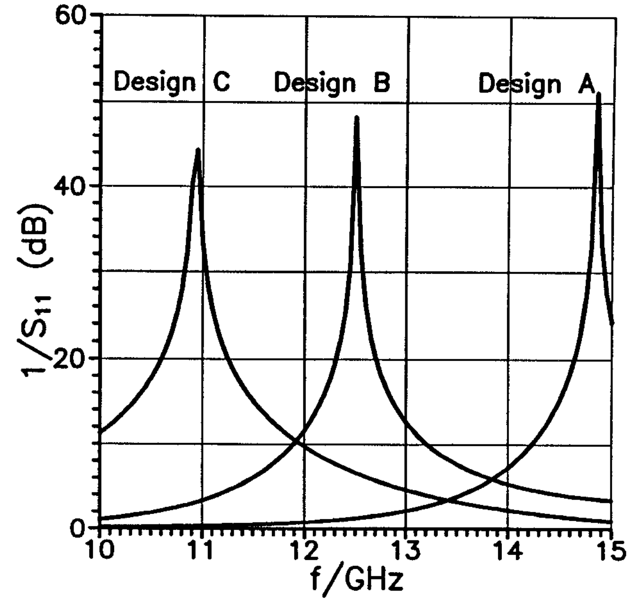


**Fig. 5** Typical return loss behavior of the three different twist profiles according to Fig. 3 (two-section designs).

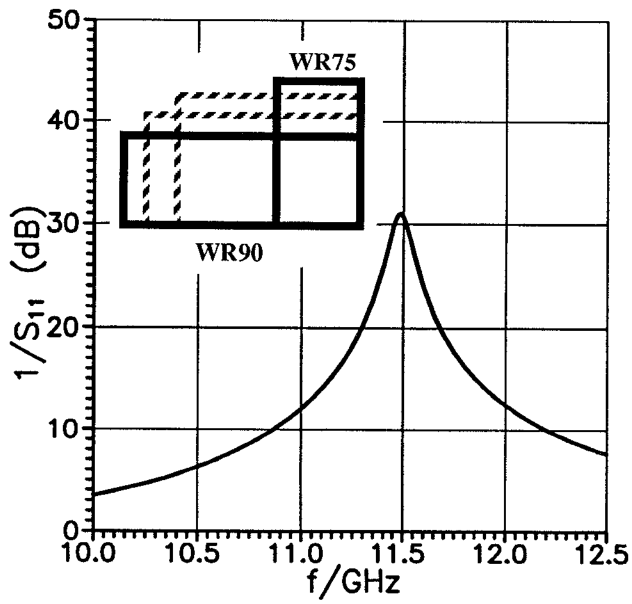


**Fig. 6** Performance of a 90° connection between X-band and WR75 waveguide.

## IV. CONCLUSIONS

The new designs of short and machinable 90° waveguide twists offer an attractive solution for integrated rectangular waveguide applications. Three different design variants cover an entire waveguide band and achieve bandwidths of up six percent. The designs are extremely short and, as an additional option, are capable of joining waveguides of different cross-sections. The mode-matching procedure used is efficient and PC operational since only purely rectangular cross-sections are utilized in the individual twist configurations. Measurements at the fundamental step discontinuity verify the theoretical model.

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