Design of integrated waveguide twist components

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Abstract: Design guidelines for single and cascaded rectangular twist components for applications in integrated waveguide technology are introduced. The structures are readily machinable by modern CNC machines. Three different design variants are developed covering twists for the lower, medium and upper frequency range of a waveguide band. Individual 90 degree twist sections are extremely short and, therefore, ideally suited for application in satellite communication waveguide bands. Only rectangular instead of L-shaped cross-sections are utilised, which significantly simplifies CAD procedures and makes software operational on personal computers. It is demonstrated that the relatively narrow bandwidth of a single 90 degree twist can be increased by cascading individual twist components. Moreover, the rectangular input and output ports can be of different cross-sections, thus eliminating the need for additional impedance transformers.

1 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 were carried out some decades ago [1, 2] whereas subsequent studies focused on the propagation characteristics of twisted rectangular guides [3–6]. Discrete twist components produced by continuously twisting a rectangular waveguide are readily available.

However, with the advent of integrated waveguide technology, where twists need to be fabricated from solid blocks of, for example, aluminium, machinability has become a critical issue. This has been addressed in Reference 7, where a continuous but varying L-shaped section is proposed which connects a rectangular waveguide to one rotated by 90 degrees. Although this approach provides a 20 dB return-loss bandwidth over approximately 50% of the waveguide Q-band, the design is rather long (in excess 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 since the eigenmode spectra of several L-shaped waveguides must be evaluated by a lengthy numerical procedure.

Therefore, a novel design together with three different design guidelines of individual 90 degree waveguide twists for integrated waveguide applications (Fig. 1*a*) are introduced in this paper. The key features of this new approach are, first, that the components are extremely short, which makes them suitable for frequencies around and below 10 GHz, secondly, that a field rotation and impedance transformation can be achieved simultaneously, and thirdly, that the twist components comprise only purely rectangular waveguide sections, which allows machinability and, at the same time, significantly simplifies the numerical analysis procedure.

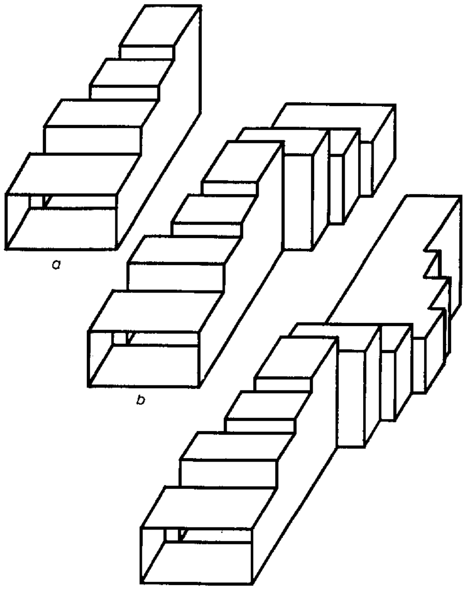

Fig. 1 *Machinable twists for integrated waveguide applications*
a 90 degrees *b* 180 degrees *c* 270 degrees

Furthermore, the only disadvantage of a single 90 degree twist, its relatively narrow bandwidth, is addressed. It is demonstrated that a single 90 degree twist provides only a single return-loss pole independent of the number of individual waveguide sections used. Bandwidth enlargement can be achieved, however, by cascading 90 degree twists to form 180 degree (Fig. 1*b*) and 270 degree (Fig. 1*c*) twist structures.

2 Theory

The analysis of the waveguide twists shown in Fig. 1 is based on mode-matching techniques [8, 9]. The basic-block discontinuity involved is depicted in Fig. 2. An intermediate region [10] of vanishing length, whose

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cross-section contains those of the two connected waveguides as subsets, is theoretically introduced in order to solve for the generalised scattering matrix of this junction. Since the structure is completely unsymmetric, the cross-section functions of TE and TM modes in the two connected waveguides $i = I, II$ and in the intermediate region $i = O$ are given by

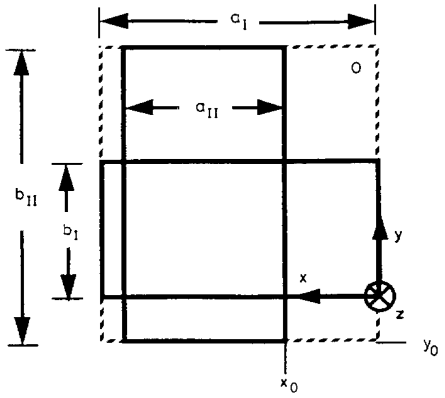

Fig. 2 *Discontinuity formed by two offset-connected 90 degree rotated rectangular waveguides. Dashed frame denotes cross-section of intermediate region*

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

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

where δ_{0k} is the Kronecker delta, and offsets x_{oi} and y_{oi} can be positive or negative depending on the individual connection of the two guides. At each individual discontinuity along the twist section, the origin is chosen to be the lower right corner of waveguide I, i.e. $x_{oI} = y_{oI} = 0$. If the discontinuity requires an intermediate region to be introduced, width a_O, height h_O and offsets x_{oO}, y_{oO} are automatically chosen so that this region covers both cross-sections of connected guides I and II. This can lead to $a_O = a_I$ and $b_O = b_{II}$ as in Fig. 2 or to $a_I < a_O < a_I + b_{II}$ as shown in the inset of Fig. 5*b*.

Once the generalised scattering matrix of a discontinuity is computed, that of the following homogeneous waveguide II of a certain length is cascaded. This forms the basic block matrix of a waveguide section. The overall scattering matrix is obtained by cascading all individual blocks [8] of the twists of Fig. 1. The CPU time for an analysis of a 270 degree rotation according to Fig. 1*c* is approximately 20 minutes on a 66 MHz 486 PC.

One of the major advantages of this concept of using single or cascaded 90 degree twists is that the length of the individual 90 degree rotation is extremely short. This has been verified by many optimisation attempts using different strategies [11]. All optimisation routines tested reduce the lengths of the individual sections in such a way that the overall length of the 90 degree twist lies between 1/16 and 3/16 of the guide wavelength at midband frequency. Therefore, even cascaded sections as shown in Fig. 1*c* are relatively short, and hence are suited to integrated waveguide applications below 20 GHz.

Guidelines for the design of three different profiles for 90 degree twist sections (Fig. 3) have been developed. Let K be the number of sections between input and output waveguide, then the section lengths are given by

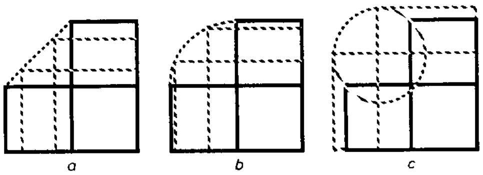

Fig. 3 *Three design variants of profiles for 90 degree twist sections*

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

where λ_{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 ($a_I \times b_I$) and output ($a_{II} \times b_{II}$) are given by

Design A

$$a_k = a_I - \frac{k}{K+1}(a_I - a_{II})$$
$$b_k = b_I + \frac{k}{K+1}(b_{II} - b_I) \tag{4}$$

Design B

$$a_k = a_{II} + (a_I - a_{II}) \cos\left(\frac{0.5\pi k}{K+1}\right)$$
$$b_k = b_I + (b_{II} - b_I) \sin\left(\frac{0.5\pi k}{K+1}\right) \tag{5}$$

Design C

$$a_k = \frac{a_I + a_{II}}{2} + R \cos\left(\phi_o + \frac{\pi k}{K+1}\right)$$
$$b_k = \frac{b_{II} + b_I}{2} + R \sin\left(\phi_o + \frac{\pi k}{K+1}\right) \tag{6}$$

where

$$R = \tfrac{1}{2}\sqrt{[(a_I - a_{II})^2 + (b_{II} - b_I)^2]}$$
$$\phi_o = -\arctan \frac{b_{II} - b_I}{a_I - a_{II}} \tag{7}$$

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

These guidelines have been tested to produce 90 degree twists of up to 6% bandwidth (20 dB return loss) in the lower frequency range of a waveguide band which reduces to less than 3% at the upper end (see results).

3 Results

First, the convergence of the theoretical approach is investigated. Fig. 4 shows a respective analysis for a two-section 90 degree twist in WR75 waveguide. The two frequencies shown correspond to the 20 dB return-loss values of a typical component, which has been designed from eqns. 3 and 5, operating near the centre of the waveguide band. Beyond 46 modes (TE + TM), the difference in input return loss is less than 1 dB which is deemed sufficient for the investigations presented here.

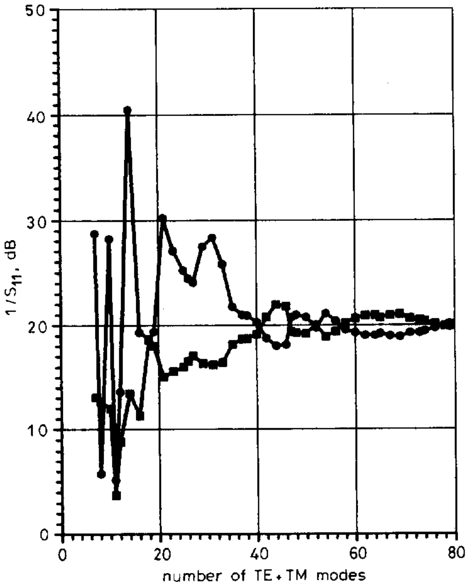

Fig. 4 *Convergence of input return loss for two-section 90 degree twist according to Fig. 1a*
—●— 12.3 GHz
—■— 12.7 GHz

Fig. 5 validates the theoretical model for the basic step discontinuity of Fig. 2. Note that the two Ku-band waveguides form a junction which generates higher reflection than the actual discontinuities involved in the twisted configurations of Fig. 1. Good agreement between theory and measurement can be observed not only for the magnitudes (Fig. 5*a*) but also for both reflection and transmission phase (Fig. 5*b*).

Fig. 6 displays the typical performances of the three different 90 degree twist design variants of Fig. 3. The 20 dB return-loss bandwidths are 6.0, 3.0 and 2.7% for designs C, B and A, respectively.

The operating principle of the stepped 90 degree waveguide twist (Fig. 1*a*) is primarily based on the conversion of the TE_{10} mode to the TE_{01} mode. It is obvious that 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 90 degree-rotated output guide fails to provide a reasonably enlarged bandwidth as is demonstrated in Fig. 7. Following the design-B strategies (initial design), the 20 dB return-loss bandwidths are 3.0% for a two-section (dotted line) and 2.9% for a five-section (dashed line) 90 degree twist. Although some improvement in bandwidth can be achieved (3.8%, solid line in Fig. 7) by employing optimisation techniques [11], on the individual section lengths, additional return-loss poles—as required for a significant increase in bandwidth—obviously cannot be created.

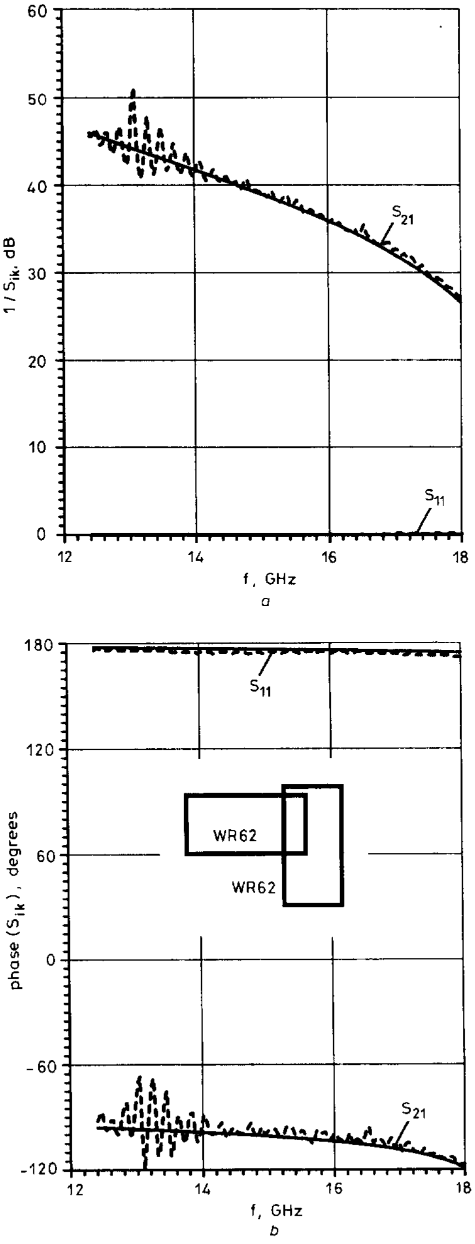

Fig. 5 *Comparison between theory (———) and measurement (– – –) at the example of a waveguide transition according to Fig. 2 in Ku-band*
a Insertion and return loss
b Reflection and transmission phase

Consequently, additional 90 degree twists must be cascaded (Fig. 1*b*, *c*) to accomplish bandwidth enlargement. This is demonstrated in Fig. 8 for a 270 degree twist according to Fig. 1*c* achieving a 20 dB return-loss bandwidth of 9%. Design guidelines B are used here for the initial 270 degree twist design. However, optimisation with respect to the individual section lengths is necessary to obtain approximately equi-ripple behaviour for a specified in-band return-loss value.

As outlined above, machinable 90 degree twists operating at the lower end of a waveguide band require twist profiles incorporating waveguide cross-sections which are enlarged compared to the input and output guide dimensions (Fig. 3, design C). Cascading two of these 90 degree twists to form a 180 degree twist component according to Fig. 1b leads to an interesting lowpass filter application as is demonstrated at an X-band example in Fig. 9*a*. Two return-loss poles (dashed line) for the two cascaded 90 degree twists (Fig. 1*b*) are obtained in the lower frequency range. Due to the enlarged cross-sections in the individual two-section twists, however, TE_{11} modes start to propagate at around 10 GHz in addition to the fundamental TE_{10} and TE_{01} modes. Therefore, each of the two 90 degree twists can be regarded as a triple-mode resonator. Obviously, cross-coupling takes place and produces the insertion-loss pole at 11.35 GHz (solid line).

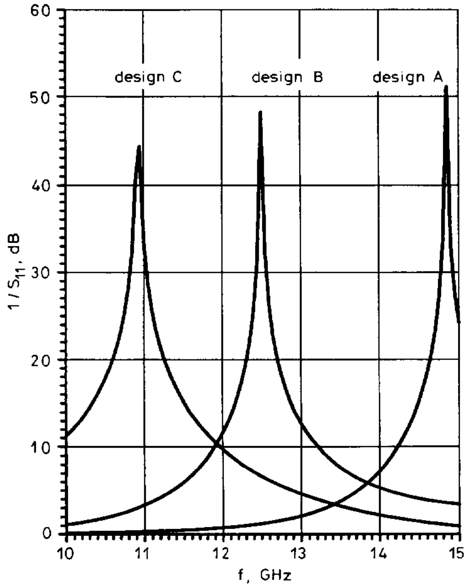

Fig. 6 *Typical return-loss behaviour of the three different 90 degree twist profiles according to Fig. 3 (two-section designs)*

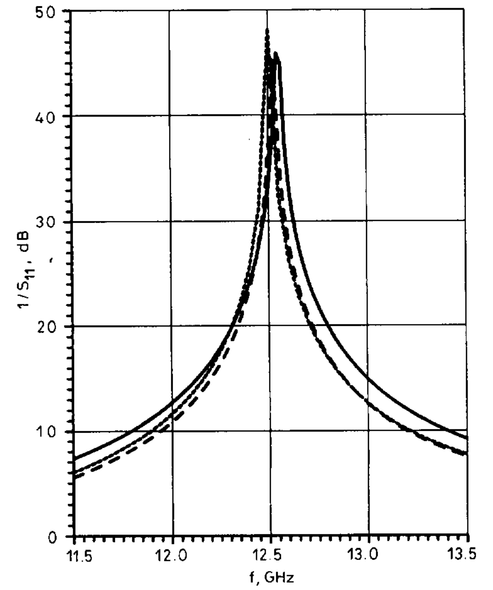

Fig. 7 *Return-loss behaviour of two-section and five-section 90° twists in WR75 waveguide according to Fig. 1a*

······· initial 2-section
- - - - initial 5-section
——— optimised 5-section

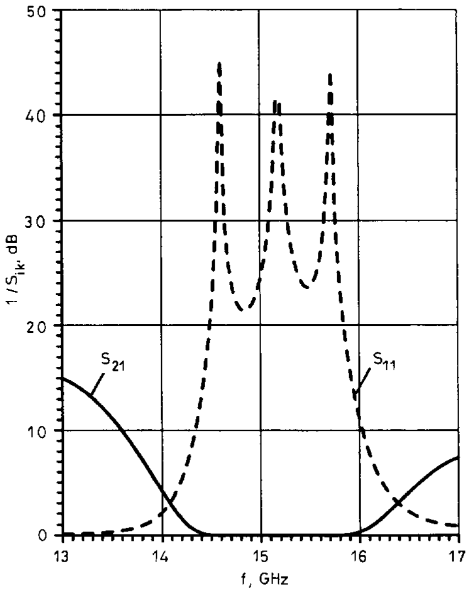

Fig. 8 *Bandwidth enlargement and return-loss pole generation by cascading three 90 degree Ku-band twists according to Fig. 1c*

Fig. 9*b* shows the performance of a 270 degree rotation (Fig. 1*c*) formed by adding one more 90 degree twist to the structure investigated in Fig. 9*a*. By optimising the individual section lengths for equi-ripple behaviour and approximately the same 3 dB frequency as in Fig. 9*a*, the 20 dB return-loss bandwidth is increased from 1.5 GHz (Fig. 9a) to 1.9 GHz (Fig. 9*b*) and the stopband pole is moved closer to the passband and appears now at 10.9 GHz (Fig. 9*b*, solid line). The dip at 11.9 GHz is caused by the cutoff frequency of the TE_{20} mode in one of the enlarged waveguide sections.

In both designs presented in Fig. 9, the waveguides connecting two 90 degree twist sections are chosen to be 22.86 mm × 11.43 mm, which are increased-height X-band waveguides. This approach seems to slightly enlarge the bandwidth of the individual 90 degree twists involved. It also demonstrates the capability of the design guidelines to connect rectangular waveguides of different cross-section dimensions (e.g. $a_I \neq b_{II}$, $b_I \neq a_{II}$) and still achieve the desired field rotation. Fig. 10 shows such an example for a 90-degree twist connecting an X-band and a WR75 waveguide. In this respect, the approach presented here can eliminate the need for additional impedance transformers between waveguide bands.

4 Conclusions

The new concept of single and cascaded rectangular twist components offers an attractive solution for integrated rectangular waveguide applications. The basic 90 degree twist sections obtained from three different design guidelines are extremely short and readily machinable by modern CNC facilities. The bandwidth of a single 90 degree rotation can be enlarged by cascading similar components. Especially at the lower end of a waveguide band, this leads to an interesting application for lowpass filtering. Since only cross-sections of purely rectangular shape are utilised, the numerical modelling procedure is based on well-defined eigenfunctions and, therefore, is operational on modern personal computers. Measurements at the fundamental step discontinuity and a convergence analysis verify the theoretical model.

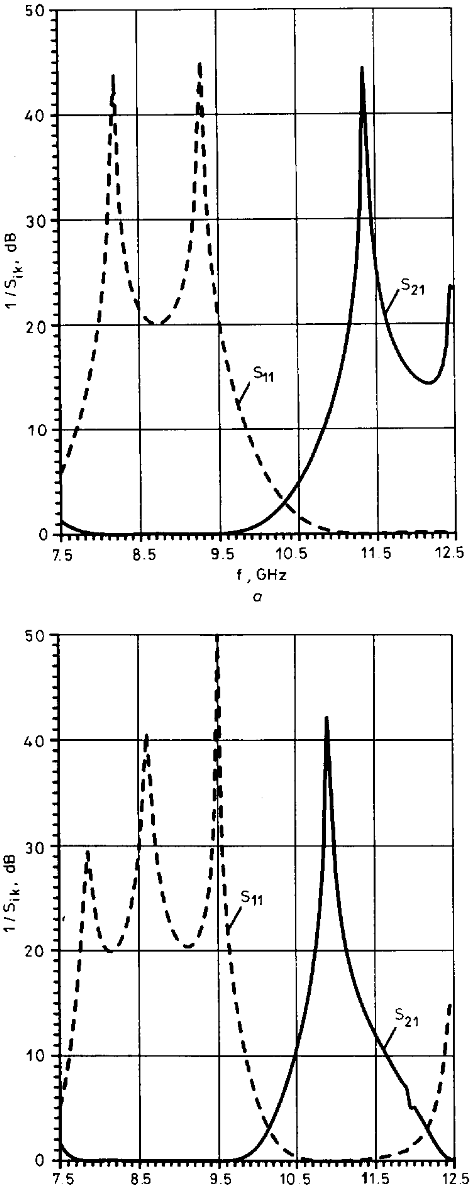

Fig. 9 *Multiple 90 degree X-band twists for lowpass filter applications*
a 180 degree according to Fig. 1*b*
b 270 degree according to Fig. 1*c*

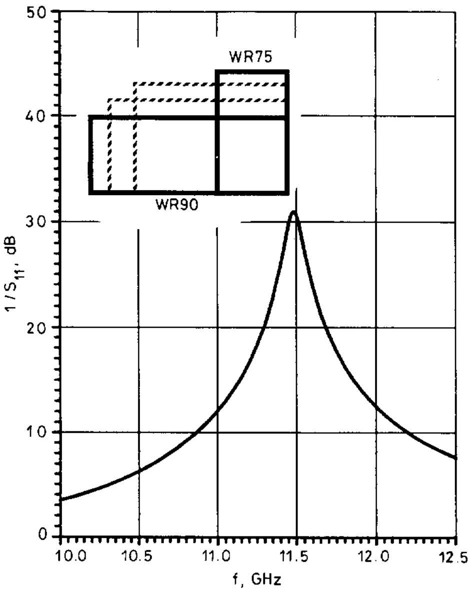

Fig. 10 *Performance of a 90-degreee connection between WR90 (X-band) and WR75 waveguide*

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