Step-Twist Waveguide Components*

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Summary—**The step twist is a number of adjoining sections of straight rectangular waveguide, twisted about their common axis at their junction faces. The technique of designing the step twist resides in the proportioning of the section dimensions and the angles at the twist faces. The resulting design is much shorter than the usual twisted waveguide; it offers further advantages in ease of specifying shape and dimensions, and in their reproducibility in construction.**

A series of fixed 90-degree step twists has been designed for the rated 40 per cent frequency bandwidths in the standard waveguide sizes for 1 to 40 kmc. The total angle is divided equally among seven faces spaced about $\frac{1}{8}$ wavelength in the guide. Each step twist is matched within 0.3 db swr with plain flanges or 0.5 db swr with choke flanges at both ends.

Rotary step twists for operation at all angles out to ±90 degrees have been designed for the same bandwidths. The total angle is divided unequally among four faces (choke flanges) spaced about $\frac{1}{4}$ wavelength in the guide. The entire unit at maximum rotation is matched within 1.2 db swr with choke flanges at both ends; the matching is closer at lesser rotation.

INTRODUCTION

Twist Section

IN ASSEMBLIES of rectangular waveguides for microwave systems, various components are needed for joining the waveguides. One of these is the twist section, either fixed or rotary. The usual fixed twist section is merely a twisted section of waveguide. There has been no rotary twist section in common use, but rather other types of rotary joints have served the purpose.

Step Twist

The step twist is a configuration suited for both fixed and rotary twist sections. It comprises two or more adjoining sections of straight rectangular waveguide that are twisted about their common axis at one or more junction faces. A typical step twist is one having a total angle of 90° divided among several faces.

Fixed Step Twist

The fixed step twist has several advantages over the twisted waveguide. It is shaped to prescribed dimensions without any deforming process so the dimensions can be realized closely by simple techniques such as cutting or die-casting. This enables a more sophisticated design compressed into a much shorter distance along the waveguide.

Rotary Step Twist

The rotary step twist has a great advantage over continuously rotatable joints if the angle of rotation can be limited to a few quadrants. It is the only type of rotary joint that propagates only the desired single mode through the rotary section. The usual rectangular waveguide guides a wave in a single linear transverse mode not suited for continuous rotation, so that objective requires transformation to circular polarization or a circular mode and back again. The circular section of waveguide propagates at least two crossed linear modes, and in the usual designs is enlarged to propagate also a circular mode utilized in the rotation. The principal problems of design are the mode transformers and the avoidance or suppression of the spurious modes. This problem is avoided in the twisting type of rotary joint.

Rated Frequency Bandwidth

It is desirable to have designs of waveguide components that operate over the entire rated frequency bands of the standard sizes of waveguide. A program of development of such components has been sponsored by the armed services under the direction of the Signal Corps Engineering Laboratories. The possibilities of step-twist components had been investigated by the writers a few years ago and had been found to be adaptable for wideband design. Therefore the components to be described were recommended for this program and have been developed as part of the program.[13] Over the rated (40 per cent) frequency bandwidth of a rectangular waveguide, these components meet the usual requirements in holding the reflection within close limits and in handling as much pulse power as other typical components for the same size waveguide. Furthermore, the step-twist components offer their peculiar advantages over other types.

Evolution of Step Twist

The idea of the step twist in rectangular waveguide was proposed in Radiation Laboratory.[3] It was a byproduct of the vertebra type of flexible waveguide, made of a series of short sections coupled by noncontact choke flanges. It was found that these sections could be twisted at the flanges to form a rotary twist joint. As in the vertebra type, it was proposed to space the twist faces by a quarter wavelength for cancellation of their reflection at the middle of the operating frequency band. Subsequently the writers developed some improved

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relationships in this type of rotary joint[5] and came to appreciate that the step twist offered advantages also in a fixed section with contact junctions at the twist faces.[6]

Designs

The step-twist components to be described have been designed for a total angle of one quadrant (90°). The rotary type operates up to this angle in either direction (±90°). In general, simpler designs can be devised for lesser angles. The same is true for lesser bandwidths, as will be exemplified by a much shorter "tuned" design of fixed step twist for 12 per cent frequency bandwidth as contrasted with the "wideband" design for 40 per cent bandwidths.

SINGLE-FACE STEP TWIST

Basic Element

The basic element of step-twist designs is the twist at a single face as shown in Fig. 1. Two abutting rectangular waveguides are joined in a plane interface with a twist angle denoted θ. The width and height of the rectangular waveguides are denoted a and b as indicated.

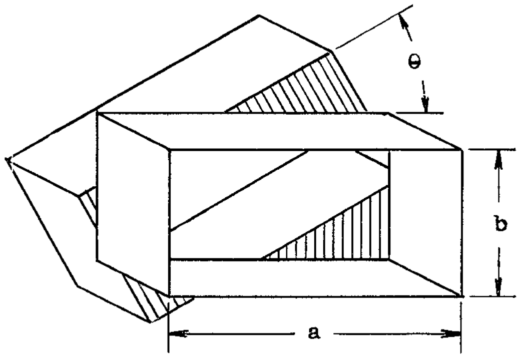

Fig. 1—Single-face step twist.

Functional Properties

The single-face step twist introduces at its junction a combination of shunt inductance, series inductance, and shunt capacitance. The shunt inductance is the predominant component, caused by the constriction of the area at the sides of the rectangular cross section. In this respect, the twist is comparable with an inductive iris or a sidewise-step offset. The area at the sides determines the normal distributed shunt inductance in the waveguide. The reduction of this area reduces the shunt inductance below the normal, which is the same as introducing another shunt inductance at the location of the junction face.

Reflection

Reflection at single-face step twist is on the hemisphere chart in Fig. 2 (next page). In rectangular waveguide of a certain aspect ratio b/a, the reflection varies with the twist angle θ and with the frequency ratio f/f_c (the operating frequency over the cutoff frequency of the size of waveguide). As is customary, the reflection coefficient is represented in terms of the standing-wave ratio (swr), denoted S and expressed in decibels (db S, meaning "db of S"). The orientation of the chart is indicated by the locus of pure shunt inductance. Fig. 2 applies quantitatively to any rectangular waveguide of the specified aspect ratio (found in 2×1-inch guide) and qualitatively to any of the standard cross sections, having an aspect ratio of $\frac{1}{2}$ or slightly less.

Variation of Reflection

As the twist angle increases from zero to 90°, the reflection coefficient increases from zero to unity. The complete reflection occurs when the two abutting guides are crossed so the normal TE-10 mode of propagation in either one appears in the other as the TE-01 mode which is not propagated at frequencies in the normal operating range. At intermediate angles, the reflection is greater at lower frequencies, nearer to cutoff. This is to be expected because shunt inductance has more effect at lower frequencies, the normal shunt inductance being one of the factors determining the cutoff frequency in waveguide.

Rated Bandwidth in Guide

The frequency ratio, in normal operation, is restricted to a range between one and two in order to assure single-mode propagation in the rectangular waveguide. In the standard waveguides, the rated range is within the limits 1.23 and 1.91 so this is the range plotted in Fig. 2.[13]

Low-Frequency Limit

The locus of pure shunt inductance (thin iris) is plotted in a semicircle in Fig. 2. It is approached in the limit as the frequency approaches cutoff ($f/f_c=1$), because the region of field distortion at the twist becomes "thin" (occupying a distance much less than the wavelength in the guide). The departure from this limit is caused by shunt capacitance and series inductance, which could be separated by further tests to determine the parameters of the equivalent two-port network.

Magnitude of Reflection

Some relations are better presented by plotting variation of magnitude of reflection coefficient with angle of twist, as in Fig. 3 (next page). The angle scale is proportional to sin $^2\theta$, which would reduce the curves to a straight line in a certain case. This case is plotted by the dashed line; its description is omitted because it is not simple and has only academic interest. In the case of a rectangular guide twisted by a small angle, this straight line is approached as the frequency is decreased toward cutoff.

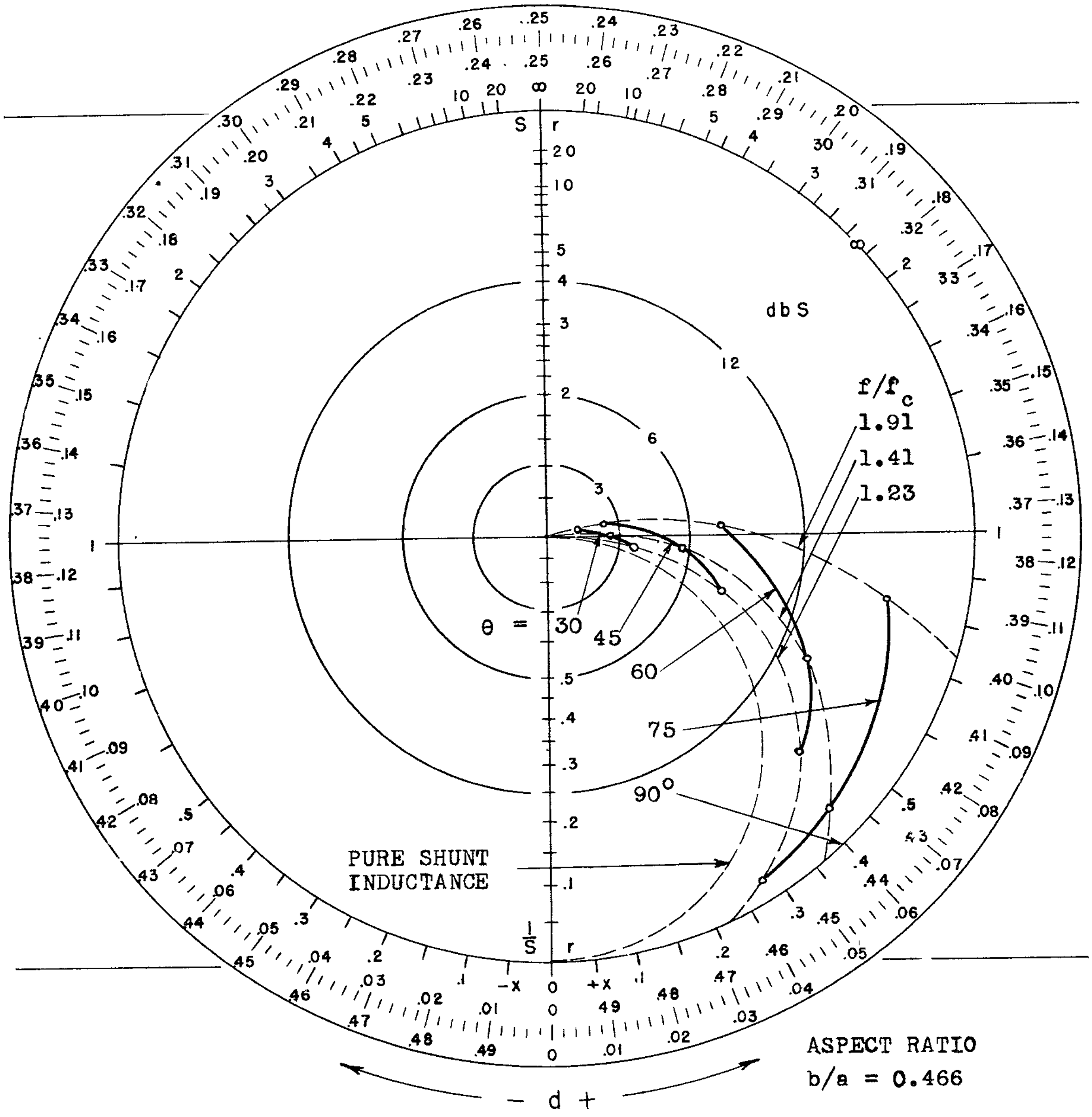

Fig. 2—Impedance of single-face step twist at all angles.

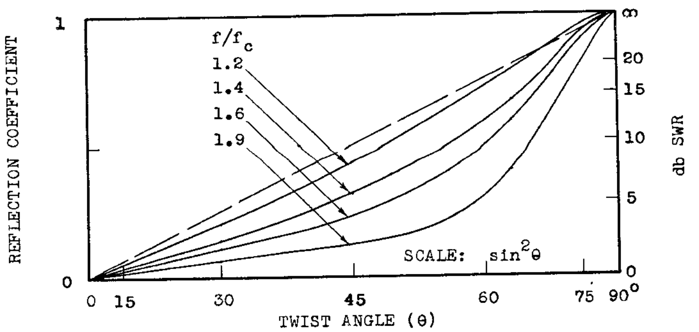

Fig. 3—Reflection by a single-face step twist.

Square Law

For small angles, perhaps up to 30°, the reflection coefficient (and also db S) is approximately proportional to the square of the angle. This is indicated by the slope of each curve approaching a constant value near the origin in Fig. 3. This relation is predicted by a simple consideration: the reflection coefficient is an even-powered function of the angle because it is the same for equal and opposite angles; therefore the first term in a series expansion would be proportional to the square of the angle. In his first work on this subject, the writer predicted this law and utilized it in the binomial rule to be presented further on. (More recent theoretical studies have indicated that the coefficient of proportionality is not quite constant, but rather has a logarithmic variation which is a minor factor not apparent in the observed curves.)

TUNED 90° STEP TWIST

Tuned or Wideband

If the wavelength bandwidth in the guide is small enough to make good use of quarter-wave spacing between twist faces, such spacing may be utilized and the design is here termed "tuned." This is to distinguish from "wideband" designs in which such spacing cannot

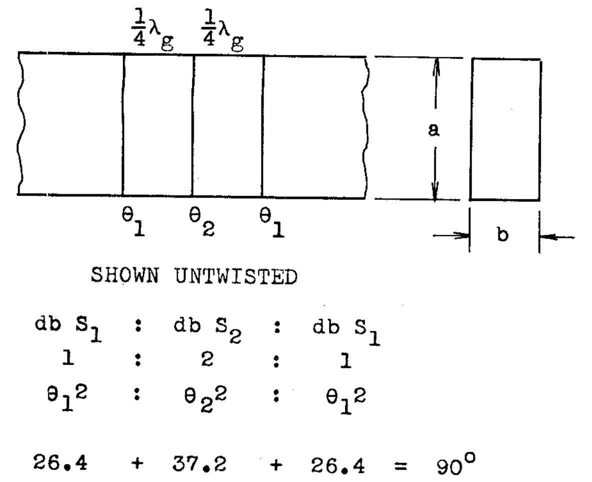

Fig. 4—Three-face 90° step twist based on binomial coefficients.

be effective over the bandwidth. If the frequency bandwidth is about 12 per cent and the guide-wavelength bandwidth about 18 per cent, such spacing is advantageous. Its utility is much less, however, if these respective bandwidths are about 40 and 80 per cent, the rated values for any one size of rectangular waveguide. While there is no critical basis for separating the "tuned" and "wideband" designs, there is a transition in the philosophy of design for guide-wavelength bandwidths less or greater than $\frac{2}{3}$ (67 per cent).

Three-Face Design

Figs. 4 and 5 are a diagram and a photograph of the first fixed step twist designed by the writers. It is a three-face 90° twist for a 12 per cent frequency bandwidth. It is a "tuned" design in that it utilizes quarter-wave separation of the twist faces, as indicated. (The wavelength in the guide is denoted λ_g as usual.) This design was conceived as a fixed version of the previous three-face rotary model which was the first step twist designed by the writers. The novel feature of this design (and the previous rotary design) is the rule of binomial coefficients applied to the multi-face step twist. The rotary type is hardly susceptible of any other form of compensation, and none other is used in this corresponding fixed model.

Binomial Rule

The binomial rule is generally recognized as a basis for reducing the reflection in certain waveguide components operating over a substantial bandwidth.[1,2] If several small bumps of the same kind are spaced at quarter-wave intervals, their resultant reflection at frequencies near the design frequency is nearly minimized by proportioning their individual reflections in the ratio of a set of "binomial coefficients." This rule provides a simple starting point for many designs, even though some departure from the rule gives the best design for substantial bumps and any substantial bandwidth. In applying the binomial rule to the step twist, it is noted again that the reflection at each face is roughly proportional to the square of the angle of twist. Therefore the angles at the respective faces are made proportional to the square roots of a set of binomial coefficients. For three faces, as shown in Fig. 4, the binomial coefficients are 1:2:1; therefore the squares of the angles are so proportioned and the angles are proportioned to $1:\sqrt{2}:1$. This gives the three angles, $26.4+37.2+26.4=90°$.

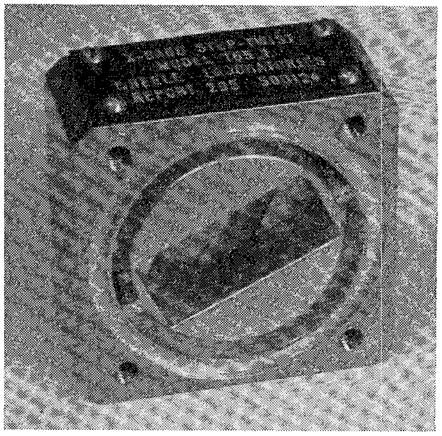

Fig. 5—Three-face 90° step twist.

Performance of Three-Face Design

The twist faces being separated only $\frac{1}{4}$ wavelength and the reflection from each being substantial (about 1.5 or 3 db swr), the quarter-wave rule fails slightly. Therefore the separation is adjusted (increased) slightly to cancel the reflection in midband. The result is a match within 0.1 db swr over the 12 per cent frequency bandwidth.

Choke Flanges

The choke flanges on the end faces, seen in Fig. 5, cause some reflection (total about 0.1 db swr for this band), especially since they are spaced by $\frac{1}{2}$ wavelength so their reflections are additive. The mentioned adjustments are made with choke flanges, so the entire unit finally is matched within 0.2 db swr. In the three-face design shown in Fig. 5, the length is minimized by locating two of the twist faces at the end flanges. This feature has limited utility because a ring resonance in the choke flange (especially at a twist face) may occur in the operating band and interfere with normal operation. In this case, the offending resonance is moved out of the band by inserting plugs in the choke groove at both sides of the guide, as seen in Fig. 5. Alternatively, there is some advantage to be obtained by adding at each end of the twist a short section in line with the abutting waveguide, avoiding any twist at the choke flange.

Large Guide

This type of 90° step twist has been made for X band (8.5–9.6 kmc) and Ku band (15.8–16.2 kmc) in "large" guide, the larger of the two sizes of waveguide rated to handle each frequency band.

Length

The length of this model, including the two choke flanges, is only 0.79 *a* or 0.68 wavelength (free-space, mid-band).

Pulse-Power Capacity

The steps increase the maximum voltage gradient, so they are rounded to leave only a small ratio of excess gradient over that in a straight guide. This leaves a pulse-power capacity in the step twist which is probably between $\frac{1}{2}$ and $\frac{1}{4}$ that of straight guide; in this respect it is comparable with other components in common use.

Construction

The three-face model is simply made of two like slabs of metal, joined back-to-back. The square external contour is the same as that of the mating plain flanges.

Utility

For moderate bandwidths, the tuned type of multiface step twist is the easiest to design, since each section may be standard waveguide of quarter wavelength midband. Further refinement may be made by compensation at each face, using expedients such as described above. In any case there is a minimum length for a reasonable number of faces among which the total angle is divided, subject to various requirements such as bandwidth, matching, and pulse-power capacity. For a single frequency, a tuned two-face design can be matched and is suitable unless greater pulse-power capacity is needed.

Wideband 90° Step Twist

Wideband Compensation

The wideband step twist to be described utilizes the principle of enlarging the width of the waveguide to compensate for the constriction at the twist faces. This compensation is nearly independent of frequency, and is here adapted to several twist faces to give a total angle of 90°.

Helical Step Twist

This study has indicated that the ideal twist section would be a smooth helix with varying angle to give a gradual transition from straight guide at the ends. The smooth surface would handle the same pulse power as straight guide. However, the smooth helix would be difficult to specify and to fabricate. It can be approximated by a step twist of many faces, which is practical to design and to construct. As a compromise, a uniform helix is approximated by twist faces of equal angles spaced about $\frac{1}{8}$ wavelength midband in the guide.

Filter Concept

The repeating step twist behaves as a wave filter made of lumped elements. It is best matched with straight guide if it has the same cutoff frequency below the operating band, so the width is enlarged to achieve this relation. In the filter in the twist section, the nearest cutoff frequency above the band is 2 or 3 times the highest operating frequency, so far removed that it has little effect in the operating band. At the junction with straight guide at each end, a midelement termination is used to minimize the transitional bump.

Enlarged Width of Guide

Fig. 6 shows the relations for a helical repeating step twist equivalent to straight guide in respect to the lower cutoff frequency and the wave impedance. It is approximately a scale drawing of the shape used. The twist angle (θ) at each face is 1/7 of 90°. All dimensions are listed on the drawing, except for a slight rounding of the edges exposed inside. A special feature is the circular contour enabling the step twist to fit in a circular cylinder.

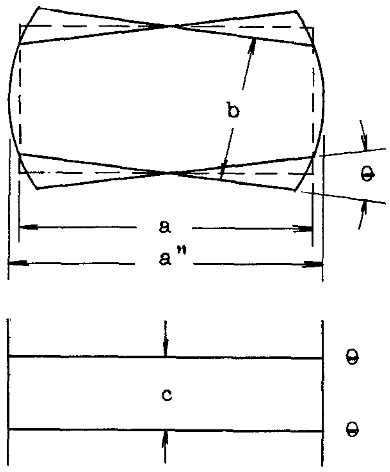

Fig. 6—Repeating step twist equivalent to straight rectangular waveguide.

Ideal Determination

The experimental determination of the proper enlargement of the guide might ideally be performed in a long helical structure by measuring the lower cutoff frequency and adjusting the width until the cutoff matches that in straight guide. Then the transition between straight guide and the long helical guide could be matched by connecting the former with a standing-wave detector and inserting in the latter a sliding termination of coaxial conical shape. This technique was not appreciated at the needed time in this development.

Actual Determination

The actual determination was made in a 90° twist section, complicated by the reflections from the junctions at both ends. At each end there may be an impedance step and a shunt susceptance. The impedance steps at both ends are opposite while the susceptances are alike. Therefore one pair cancels and the other pair adds if the twist section is a multiple of $\frac{1}{4}$ wavelength in the guide. This enables the two kinds of bumps to be separated by interpretation of the impedance locus at one end plotted on the hemisphere chart. The enlargement of the width (to diamter a'') is adjusted to nullify the impedance step (on the vertical axis of the chart) and the midelement termination (yet to be described) is adjusted to nullify the susceptance (on the horizontal axis). The result is a remarkably close match over the entire rated bandwidth of the waveguide.

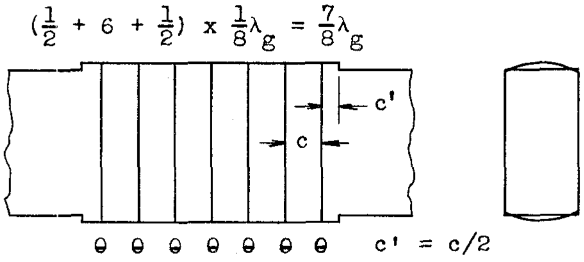

Fig. 7—Wideband 90° step twist, midseries termination.

Mid-Series Terminations

Fig. 7 is a diagram of a complete 90° step twist with the midseries terminations finally adopted. Each midseries termination comprises half a section of waveguide with enlarged width at each end. In the design procedure, this half-section is easily adjusted in length (c') to cancel the junction susceptance at midband. The 7 twist faces have equal angles (θ). The end half-sections are aligned with the straight guide and have the same height (b) so they are well adapted for choke flanges. In this manner, the entire length between the flanges is utilized in the helical step-twist filter.

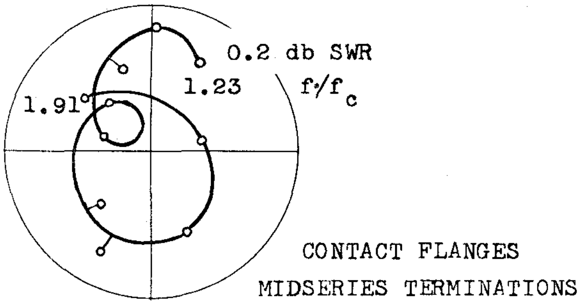

Fig. 8—Impedance of experimental wideband 90° step twist.

Performance

Fig. 8 shows the residual reflection of this design (with contact flanges) by the impedance plot on the hemisphere chart (greatly enlarged). The reflection is less than 0.2 db swr over the entire rated frequency band of the waveguide. A single choke flange presents about 0.2 db swr at the edges of the band, but the pair of choke flanges is partly compensated by the twist section and by the relation between the two ends. The final models with choke flanges at both ends are matched within 0.5 db swr over the band.

Comparison with Twisted Waveguide

Since the step twist is intended to offer an improvement over the simple twisted waveguide, the two types should be compared in performance and structure. Fig. 9 shows a comparison of the reflection of the step twist plotted in Fig. 8 and a typical twisted guide, both tested with contact flanges. The latter is 3.4 times as long, but its reflection is much greater (up to 0.5 db swr as compared with 0.2 db). In favor of the twisted guide are several features: present availability; cheaper construction; lighter weight; greater pulse-power capacity (nearly the same as straight guide). In favor of the step twist are: shorter length; closer match. With further development, the step twist may acquire some of the advantages now attributed to the older type. Its pulse-power capacity is adequate for most purposes; it is estimated to be half that of straight waveguide. In the larger sizes of waveguide, the step twist may be made of thin walls and then may acquire the advantage of lighter weight; also the customary use of contact flanges will preserve the close matching of the experimental model (within 0.2 db swr).

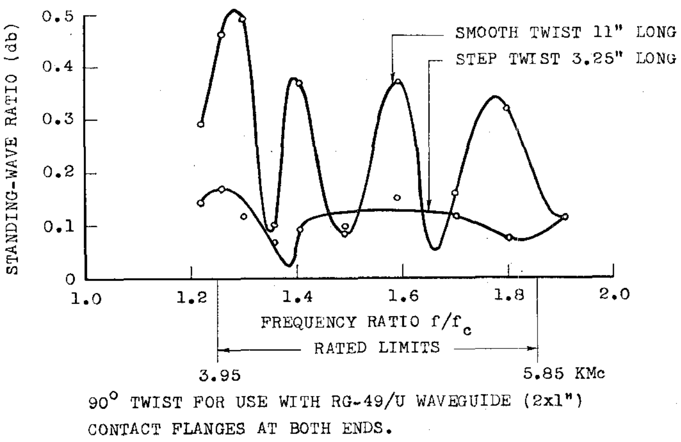

Fig. 9—Comparison of swr of smooth twist and step twist.

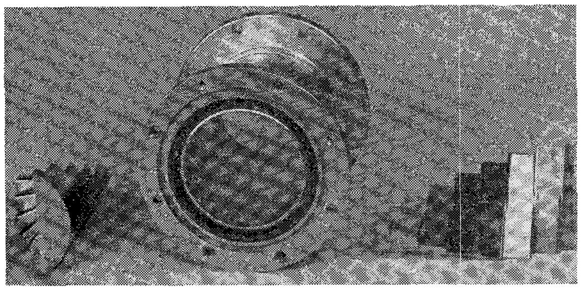

Fig. 10—Wideband step twist, disassembled.

Construction

The final model is made of three parts, as shown disassembled in Fig. 10. An outer cylinder carries the flanges, one choke flange and one plain flange in this case. Also it provides the side walls of the waveguide in the twist section. The stepped walls are provided by two inserts, each machined as one piece on the turntable of a milling machine, using micrometer adjustments for all cuts. The exposed edges are rounded by hand. In quantity production, this piece might be made by die casting. Finally the inserts are soldered in the cylinder and the assembly is plated.

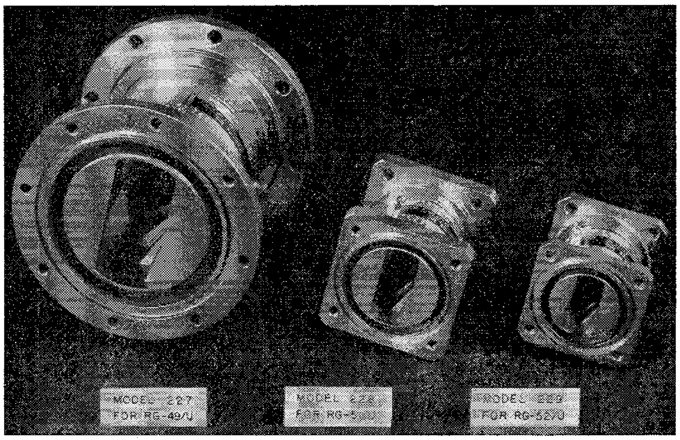

Fig. 11—Fixed 90° wideband step twist, final models.

Models

Fig. 11 shows the final models in three of the smaller sizes, having choke flanges on the near ends and plain flanges on the far ends. These models have the twist of a right-hand screw, which is provided unless otherwise specified. (The model shown in Fig. 5 happens to have a left-hand twist.)

ROTARY 90° STEP TWIST

Rotary Structure

The rotary 90° step twist is one that can be rotated through all angles from 90° left-hand to 90° right-hand, a total rotation of 180°.

The design to be described has four twist faces for operation over the rated frequency band of any one size of rectangular waveguide.

Normal Cross-Section

The enlargement of the waveguide width, used for compensation in a step twist of fixed angle, would be effective only at certain angles in a rotary step twist. In the rotary design, such enlargement is not used. All sections are made of normal rectangular waveguide cross section so, at zero angle of twist, the assembly behaves like a straight continuation of the waveguide. Even at zero angle, however, there is a substantial reflection caused by the total of six choke flanges, including two flanges at the ends and four flanges at the twist faces.

Choke Flanges

The standard choke flange has a groove about $\frac{1}{4}$ wavelength in depth. The use of this type of flange requires that the twist faces have a spacing greater than the depth of the groove. This is accomplished by separating the twist faces by $\frac{1}{4}$ the midband guide wavelength (λ_g, the average of the guide wavelengths at both extremes of the rated frequency band).

Four-Face Compromise

The use of four faces is a compromise among various factors. A longer design with more faces would give less reflection from the twisting; a shorter design with fewer faces would give less reflection from the choke flanges and would save space. The earlier design of rotary step twist had utilized three twist faces to operate over angles up to ±70° over a frequency bandwidth of 12 per cent with reflection within 0.7 db swr;[5] it was estimated that the extended requirements of the present design could be met by going to four twist faces and a better division of the angle among the faces. This proved to be correct.

Ratio of Angles

There is an optimum division of the total angle among the twist faces to minimize the upper limit of reflection over the range of angle and frequency. This optimum is believed to be somewhere between equipartition and the binomial rule of partition used in the earliest design, and some evidence to this effect has been obtained by the experiments leading to this design. The binomial rule for four faces would divide the total angle in the proportion of $1:\sqrt{3}:\sqrt{3}:1$. As an experimental approximation to the optimum, the proportion of $1:\sqrt{2}:\sqrt{2}:1$ is used in the present design, as indicated in the following table.

Binomial series:	$1 : 3 : 3 : 1$
Series used:	$1 : 2 : 2 : 1$
Ratio of angles:	$1 : \sqrt{2} : \sqrt{2} : 1$
Angles:	$90° = 18.6 + 26.4 + 26.4 + 18.6$

Reflection

Fig. 12 shows the reflection of the rotary step twist at an angle of 90°, where the reflection is greatest. The solid curve (1.25–1.86) covers the rated bandwidth of the waveguide used in the test (2×1 inches), indicating a reflection less than 1.2 db swr. The loops in the curves are typical of an optimum design; they are preferable to the single cusp obtainable by the binomial design. The final models made in two sizes (2×1 inches and $1\times\frac{1}{2}$ inches) tested within 1 db swr at 90° angle.

Models

Fig. 13 shows the model for 2×1-inch waveguide. The two parts are the outer shell and inner core, the former including one end choke flange, the latter including all the choke flanges at the twist faces. The core view shows the slotted metal strip which engages pins in all the sections to control their relative angles of rotation.

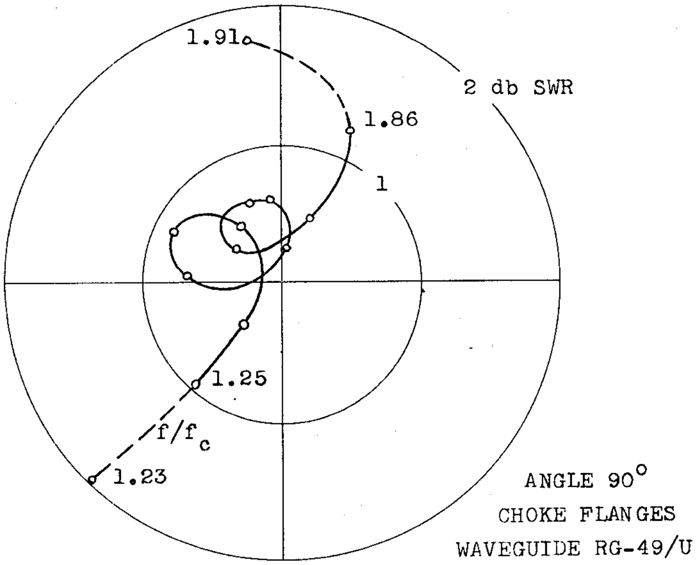

Fig. 12—Impedance of experimental rotary step twist.

Utility

The rotary step twist is probably the only motional joint that has been designed to cover the rated bandwidth of rectangular waveguide. Its pulse-power capacity is probably limited by the twisted choke flanges, a more severe limitation than the end choke flanges. Its pulse-power capacity may be about $\frac{1}{4}$ that of straight guide. This type is suitable for any reasonable angles of limited rotation as distinguished from continuous rotation. It is particularly convenient if the adjoining waveguides are in line. All contours are readily specified for fabrication.

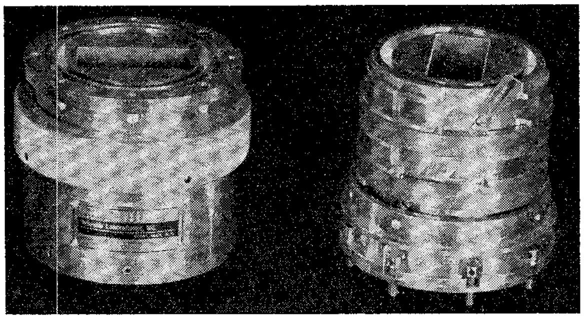

Fig. 13—Rotary step twist, partially assembled.

CONCLUSION

The idea of a step twist in a waveguide has been developed into several types of fixed and rotary step-twist waveguide components. These types are easily adapted to meet a variety of requirements. Any required angle of twist may be obtained in the shortest section consistent with the requirements of frequency bandwidth, purity of transmission (by reduction of reflection), and simplicity of design (by reduction of the number of steps and by equalization of the steps). Certain designs of fixed and rotary 90° step-twist sections have been completed for standardized sizes of waveguides, each design operating over the rated bandwidth of one size with unusual purity of transmission. Each section is much shorter than the ordinary twisted waveguide previously used for fixed angles up to 90°. Most important are the several rules for design that have been stated and tested. Nearly optimum compromise can be computed and then requires very few experimental adjustments of dimensions (none in some cases). Geometry of essential contours is simple so shapes and dimensions are easily specified and realized in construction.

The designs of 90° step-twist sections for the rated bandwidths of waveguides have been made for the Components and Materials Branch of the Signal Corps Engineering Laboratories, Squier Signal Laboratory, Fort Monmouth, N. J. It is desired to acknowledge the supervision of their engineers, especially Messrs. Abe Zeitz and Leonard B. Moore. This agency, through its Office of Technical Information, makes available on request, copies of drawings of these designs, complete with dimensions for various sizes of waveguides. Any request should refer to contract number DA36-039sc-5575.

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BIBLIOGRAPHY

[1] Slater, J. C., "Microwave Transmission," McGraw-Hill Book Co., 1942. (Multiple-quarter-wave transformer, binomial rule, pp. 57–61.)
[2] Selgin, P. J., "Electrical Transmission in Steady State," McGraw-Hill Book Co., 1946. (Binomial rule, multiple-quarter-wave transformers, pp. 194–207, 329–332.)
[3] Ragan, G. L., "Microwave Transmission Circuits," Radiation Laboratories Series, Vol. 9 (1948). (Vertebra-type flexible waveguide and rotary step twist, ±30° rotation, pp. 294–303, 433–438.)
[4] Wheeler, H. A., "Geometric Relations in Circle Diagrams of Transmission-Line Impedance," Wheeler Monographs, No. 4 (July 1948). In book, Vol. I, 1953. (Hemisphere chart.)
[5] Schwiebert, Henry, "Preliminary Mechanical Dimensions of X-Band Large Angle L-Joint," Wheeler Laboratories Report 226 to Bell Telephone Laboratories, February 18, 1949. (Rotary step twist with 3 faces, binomial rule for ±70° rotation, matched within 0.7 db swr over 12 per cent X band.)
[6] Schwiebert, Henry, "X-Band Waveguide Step Twist," Wheeler Laboratories, Report 295, January 24, 1950. (Fixed 90° three-face step twist matched within 0.2 db swr over the 12 per cent X band.) See also Report 604, December 28, 1953, and Report 606, January 8, 1954.
[7] Schwiebert, Henry, "Ku-Band Waveguide Step Twist," Wheeler Laboratories Report 410, March 27, 1950. (Fixed 90° three-face step twist matched within 0.3 db swr over the band from 16.2 to 16.8 kmc.)

[8] "Broadband Waveguide Couplings," Sperry Gyroscope Co. Report 5224-1184, April, 1950. (Choke flanges.)
[9] Smullin, L. D., and Glass, W. G., "The Offset Waveguide Junction as a Reactive Element," MIT Research Lab. of Electronics, Report 164, September 13, 1950. Also: *Journal of Applied Physics*, Vol. 22 (September, 1952), pp. 1124–1127.
[10] Spencer, N. A., "S-Band Polarization Twister," Wheeler Laboratories Report 450, February 7, 1951. (Includes rotary step-twist with single face for ±22.5° rotation, and compensating fixed steptwist for 22.5° to obtain 0 or 45° angle.)
[11] Schwiebert, Henry, and Wheeler, H. A., "Step-Twist Waveguide Components" (summary). PROCEEDINGS OF THE I.R.E., Vol. 40 (February, 1952), p. 221.
[12] Editor, "Specialized Microwave Plumbing," *Radio & Television News*, Vol. 47, No. 5, Radio-Electronics Engineering Edition, (May, 1952) pp. 1, 14–15, 52. (Fixed 90° step twist, 2 models, photos and text: [11], [13].)
[13] Schwiebert, Henry, and Van Davelaar, F. S., "Step-Twist Waveguide Components." Wheeler Laboratories Report 532 to to Signal Corps Engineering Labs., October, 1952. (Also progress reports 476, 491, 511.)
[14] Wheeler, H. A., "Pulse-Power Chart for Waveguides and Coaxial Lines," Wheeler Monographs, No. 16, April, 1953. (Table of standard waveguides, including aspect ratio.)
[15] Andrews, C. L., "Demonstrations with Microwave Wave Guides." Cenco News Chats, Central Scientific Company, Chicago, No. 77, (1953), pp. 3–6. (Step twist made of woodblock with metal surfaces.)
[16] Wheeler Laboratories, "Step-Twist Waveguide," PROCEEDINGS OF THE IRE, Vol. 42, No. 2 (February, 1954), front cover.
[17] Wheeler, H. A., "Conformal Mapping of Fields," Wheeler Laboratories Report 623, April, 1954. (Properties of steps, logarithmic coefficient in square law of reflection.)

A Double-Ground-Plane Strip-Line System for Microwaves*

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Summary—**The double-ground-plane strip line consists of two parallel conducting planes with a conducting strip imbedded in a homogeneous dielectric between them. Transmission characteristics for this system are calculated, and design formula are given. Practical viewpoints on design and application of strip lines are discussed. System can be used as an inexpensive base for microwave circuits and is well adapted to laboratory experiments and mass production.**

LIST OF SYMBOLS

ϵ_0 = Absolute permittivity of free space, farads/m.
ϵ = Relative permittivity of dielectric in the line.
δ = Dielectric loss angle.
σ = Conductivity, mhos/m.
μ_0 = Absolute permeability of free space, henrys/m.
e = Base of natural logarithms.
λ_0 = Wavelength for transmission in free space, m.
λ = Wavelength along the line, m.
f = Frequency, cps.
Z_0 = Characteristic impedance, ohms.
C = Capacitance per unit length of the line, farads/m.
b = Width of strip, m.
$2h$ = Distance between ground planes, m.
d = Thickness of strip, m.
t = Width of ground planes, m.
E = Electric force, volts/m.
E_h = Homogeneous electric force far from the edge of a very wide strip, volts/m.
P_c = Power loss per unit length of the conductors, watts/m.
P_T = Power transmitted along the line, watts.
α_d = Dielectric attenuation, db/wavelength.
α_c = Conductor attenuation, db/m.
V = Potential difference between the ground planes and the strip, volts.

INTRODUCTION

DURING the last few years there has been considerable interest in new, simpler methods for manufacturing microwave circuits. In December, 1952, the Federal Telecommunication Laboratories presented an extensive report on a microwave printed-line system [1–3]. Although it is simple enough and has proved to be very useful for many circuits, it has the disadvantage of being an open system and is thus subject to some radiation. A shielded strip-line system was described by Barrett and Barnes, [4] but no real analysis was given.

The double-ground-plane strip line described in the paper has a thin strip of copper foil placed between two sheets of low-loss dielectric, and the outer sides of the dielectric sheets are covered with conducting planes.

The following analysis described provides a theory for the double-ground-plane strip line similar to that given in [2].

TRANSMISSION CHARACTERISTICS OF THE DOUBLE-GROUND-PLANE STRIP LINE

Interest is centered particularly on the phase wavelength, characteristic impedance and attenuation of the strip line.

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