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[21]	Appl. No.	754,700
[22]	Filed	Aug. 22, 1968
[45]	Patented	Mar. 9, 1971
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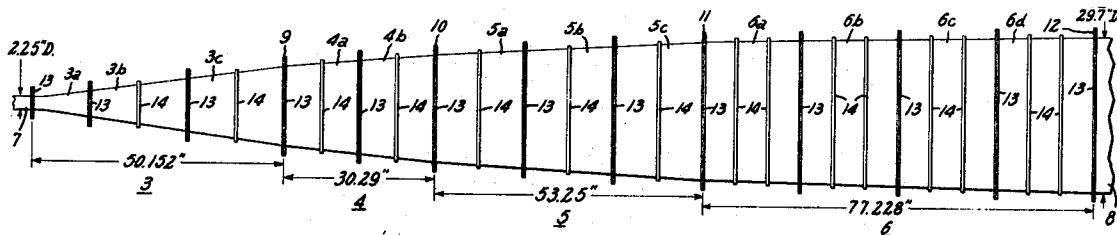
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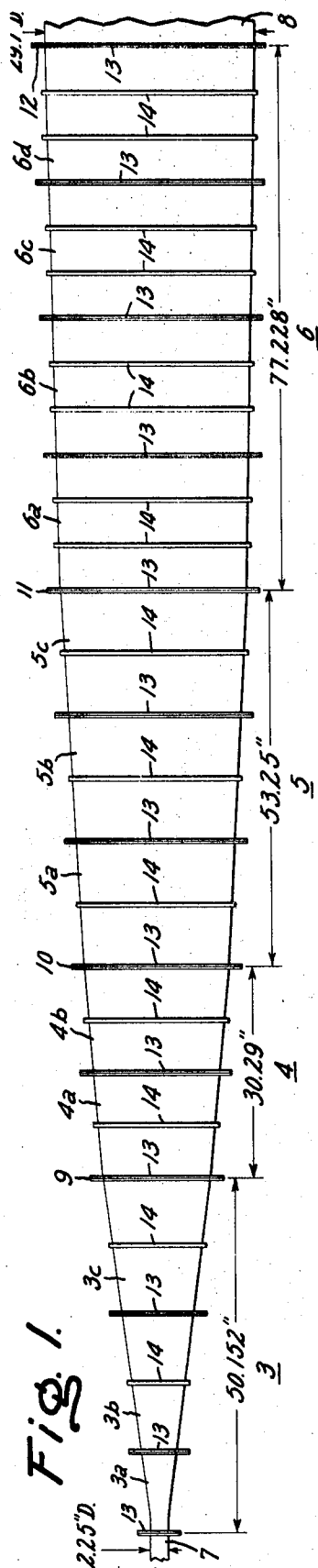
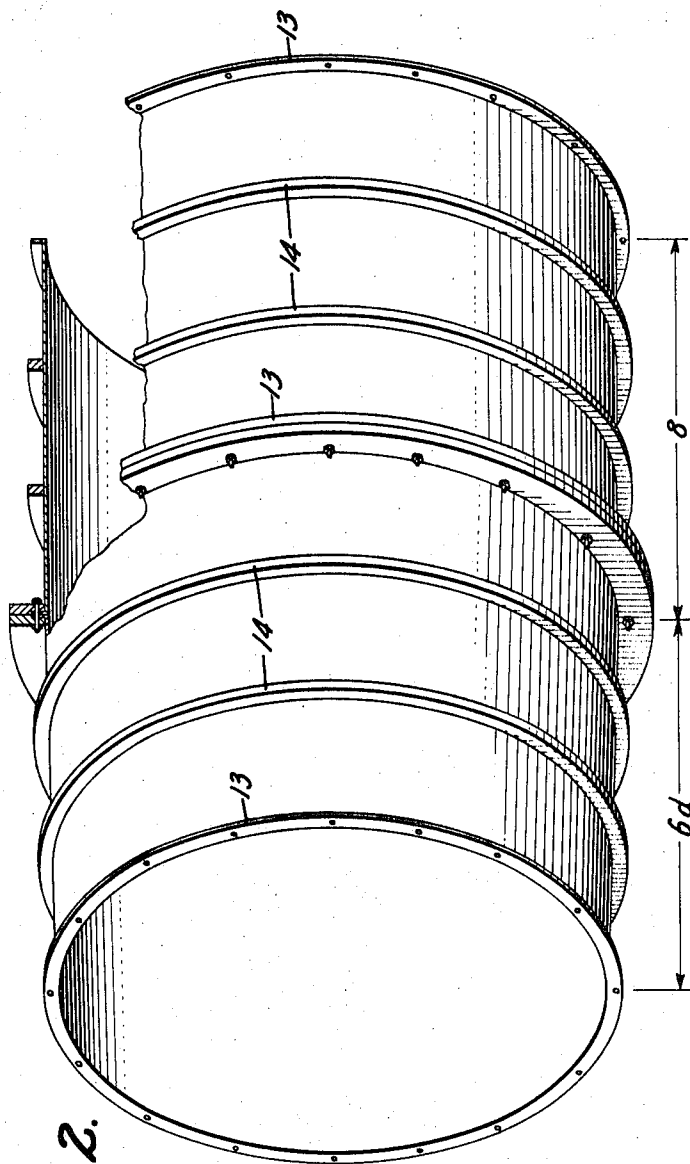
[54] WAVEGUIDE TAPER OF MINIMUM LENGTH
7 Claims, 2 Drawing Figs.

[52]	U.S. Cl.....	333/34, 333/98
[51]	Int. Cl.....	H01p 1/16, H01p 5/00
[50]	Field of Search.....	333/34, 95, 98, 98 (M)

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WAVEGUIDE TAPER OF MINIMUM LENGTH

My invention relates to a waveguide component for interconnecting two circular waveguides which differ substantially in size and method of fabrication thereof, and in particular, to a waveguide taper of minimum length for interconnecting a 2.25-diameter input waveguide to an oversize 29.7-inch diameter output waveguide adapted for propagating the TE_{01}^o mode at X-band frequency. The invention herein described was made in the course of or under a contract Af30 (602) 3810 with the Department of the Air Force.

Waveguides are conventionally employed for the propagation of lower power level signals in the microwave frequency band, that is, for the propagation of communication-type signals. Recently, it has been suggested that waveguides may also be utilized as low-loss, high efficiency transmission devices for transmission of bulk electric power. The use of waveguides for the transmission and control of very high average power at C.W. microwave frequency requires the use of oversize waveguides to obtain a low-loss transmission line. It is evident that the transmission of bulk power in the order of 10^7 watts of power through a waveguide may cause considerable heating thereof unless the waveguide attenuation is reduced by approximately four orders of magnitude as compared to the attenuation characteristics of conventional size waveguides. The reduced attenuation, in the order of 2.1×10^{-6} db. per foot, is obtained for the transmission of power in the TE_{01}^o mode at X-band frequency in an oversize circular aluminum waveguide of 29.7-inch diameter.

Although the use of oversize waveguides is feasible for the transmission of bulk power at C.W. microwave frequencies, the application may be limited by other waveguide components in the microwave system. The input end of the microwave system comprises a source for generating the bulk power microwaves and an input waveguide connected to such source. A waveguide device, commonly described as a waveguide taper, is utilized to interconnect the input waveguide to the oversize waveguide utilized in the transmission of the microwaves. In the case of propagation of the TE_{01}^o mode at X-band (5,200 to 10,900 MHz.), and in particular, operation at a frequency of 8,3500 MHz., an oversize circular waveguide having an inner diameter of 29.7 inches has been found to have suitable characteristics such as low conductivity losses. The diameter of the input waveguide is governed by the size of the TE_{01}^o mode transducer at the input thereof, and at X-band such transducers have diameters of 1.3 to 2.8 inches. A suitable transducer has a diameter of 2.25 inches. Thus, the waveguide taper device must be adapted for interconnecting waveguides having diameters of 2.25 and 29.7 inches. A waveguide taper suitable for this application has a continuously variable taper to provide desired low mode conversion, but it has a minimum length of approximately 30 ft. The fabrication costs of such a long, continuously variable taper are excessive. Thus, in order to have bulk power transmission of microwaves economically feasible, it is necessary to provide a minimum length waveguide taper for interconnecting two circular waveguides differing substantially in size, having low mode conversion losses, and capable of fabrication economically.

Therefore, one of the principal objects of my invention is to provide a waveguide taper of minimum length for interconnecting two circular waveguides differing substantially in size.

A further object of my invention is to construct the waveguide taper from a plurality of conical waveguide sections which provide interlaced pairs of mode-converting junctions having a canceling effect on the spurious modes generated at such junctions.

Briefly stated, my invention is a waveguide taper constructed from a plurality of thin wall conical waveguide sections. For the particular application wherein the waveguide taper interconnects an oversize circular waveguide to a small diameter input waveguide, four different taper angles are employed. For ease of fabrication, each conical section is further comprised of two to four sections providing a total of 12 conical sections. Adjacent sections are connected by flanges, and

stiffening rings are utilized to assure circularity of cross section of each waveguide section. The larger diameter waveguide sections are fabricated by rolling aluminum sheet metal into the desired conical shape and longitudinal welding of such sections. The sections are precisely aligned by optical means prior to being connected by means of the flanges.

The features of my invention which I desire to protect herein are pointed out with particularity in the appended claims. The invention itself, however, both as to its organization and method of operation, together with further objects and advantages thereof, may best be understood by reference to the following description taken in connection with accompanying drawing, wherein like parts in each of the several FIGS. are identified by the same reference character and wherein:

FIG. 1 is a side view of the waveguide taper constructed in accordance with my invention; and

FIG. 2 is a perspective view, partly in section, of the largest diameter taper section and section of the oversize circular waveguide connected thereto.

Referring now in particular to FIG. 1, there is shown my waveguide taper structure interconnecting a small diameter input circular waveguide 7 with an oversize circular waveguide 8. The waveguide taper comprises four conical sections each indicated as a whole by numerals 3, 4, 5 and 6, each section having a different taper angle varying from the largest angle at the small diameter end to the smallest taper angle at the large diameter end of the waveguide taper. Each section is further comprised of a plurality of short length, conical waveguide sections for purposes of reducing the fabrication costs. My waveguide taper device can be fabricated from only four separate sections, but an appreciably higher cost than by my preferred low-cost method of fabrication utilizing the short length sections to be described hereinafter. Obviously, my waveguide taper can even be constructed from a single piece of metal but at such high cost that it would be economically unfeasible for application in bulk power transmission. Since one of the objects of my invention is to provide a low-cost taper device, a waveguide taper comprising a plurality of short length, conical sections hereinafter described is one aspect of my invention. As is well known in the waveguide art, mode conversion losses are caused by spurious or undesired modes generated at waveguide junctions having abrupt changes in taper angle. Thus, another aspect of my invention is the use of four conical sections providing two pairs of mode conversion junctions which are interlaced (cascaded) such that the first and third junction effects and second and fourth junction effects each cancel as a pair. The first (cone-cone junction 9 is the junction of conical sections 3 and 4, the second (cone-cone) junction 10 is the junction of conical sections 4 and 5, the third (cone-cone) junction 11 is the junction of conical sections 5 and 6, and the fourth (cone-circular waveguide) junction 12 is the junction of conical section 6 and the oversize circular waveguide 8.

The dimension of the large diameter end of my waveguide taper is equal to the diameter of the oversize aluminum waveguide 8. The diameter of waveguide 8 is determined approximately by factors such as attenuation, power capacity and waveguide heating. For the dominant (desired) mode of propagation, TE_{01}^o , at a frequency of 8350 MHz., and desired characteristics of attenuation = 2.1×10^{-6} db./ft., maximum power capacity = $2.34 \times 10^7 \sqrt{k}$ watts where k = waveguide conductivity relative to copper, and waveguide surface heating = 1 watt/ft.², the approximate waveguide diameter is 30 inches. The exact dimension of waveguide 8 is determined by considerations of undesired resonances near the cutoff frequency of the highest order modes which may be generated by the junction and propagated in the oversize waveguide. For the particular case of TE_{01}^o being the dominant mode of propagation, the $TE_{0,21}^o$ and $TE_{0,20}^o$ modes may produce the undesired resonances. A diameter of 29.7 inches for the oversize circular waveguide 8 and operating frequency of 8350 MHz. results in the $TE_{0,21}^o$ mode being below cutoff by approximately

1 percent and the $TE_{0,20}^o$ mode being above cutoff by approximately 4 percent thereby preventing the propagation of the $TE_{0,21}^o$ mode, and to provide for the $TE_{0,20}^o$ mode waveguide wavelength which is not excessively long and a wave impedance which is not excessively high. The input waveguide 7 is assumed to have a diameter of 2.25 inches for the particular microwave system herein described. Thus, the particular waveguide taper device constructed in accordance with my invention is adapted to connect a 2.25-inch diameter input waveguide to a 29.7-inch diameter oversize waveguide supporting a $TE_{0,1}^o$ mode at X-band.

The essential data for developing a waveguide taper comprising multiple cone sections are the magnitude and phase of the mode conversion coefficients between the incident $TE_{0,1}^o$ mode and the spurious $TE_{0,n}^o$ modes. Although mode conversion results in many spurious modes being generated at the four junctions 9, 10, 11, 12 of my waveguide taper, the mode of greatest concern is the $TE_{0,2}^o$ since its amplitude is the largest of all the spurious modes.

By assuming that (a) it is the change in phase front curvature at a junction which generates the higher order modes, and (b) the boundary conditions are matched, it can be shown for graphical considerations that the mode coupling C_{12} between the $TE_{0,1}^o$ and $TE_{0,2}^o$ modes is approximately

$$|C_{12}| \doteq \frac{\pi}{8} (D/2) \Delta\phi \quad (1)$$

where $\Delta\theta$ is the change in half-cone angle of the taper in radians, and D is the diameter at the junction. $|C_{12}|$ is the mode conversion amplitude or magnitude of the mode coefficient. The phase of the mode conversion coefficient is $\pm\pi/2$ for small values of $\Delta\theta$.

A basic design principle of a multi-conical taper is that the complex sum of all the mode conversions occurring at the junctions between the adjacent cones (and cone-circular waveguide) add to a sufficiently small value within the frequency band of interest. In order to obtain this computation, the differential phase constant $\Delta\beta_{1n}$ between the $TE_{0,1}^o$ and $TE_{0,n}^o$ modes must be known as a function of diameter within the taper. The differential phase constant, also known as the differential phase velocity or phase shift between the desired $TE_{0,1}^o$ mode and the undesired higher order $TE_{0,n}^o$ modes is calculated from the following equations:

$$\Delta\beta_{1n} = \beta_1 - \beta_n \quad (2)$$

$$= \frac{2\pi}{\lambda_{c1}} - \frac{2\pi}{\lambda_{cn}}, \text{ radians/length} \quad (3)$$

$$= \frac{360}{\lambda} [\sqrt{1 - (\lambda/\lambda_{c1})^2} - \sqrt{1 - (\lambda/\lambda_{cn})^2}] \quad (4)$$

degrees/length

wherein λ is the operating frequency free space wavelength;

λ_{c1} is the cutoff frequency wavelength of the $TE_{0,1}^o$ mode, equal to $0.82 D$, D is the waveguide diameter;

λ_{cn} is the cutoff frequency wavelength of the undesired higher order $TE_{0,n}^o$ mode,

λ_{g1} is waveguide wavelength of the $TE_{0,1}^o$ mode in waveguide with diameter D ; and

λ_{gn} is a waveguide wavelength of the $TE_{0,n}^o$ mode in waveguide with diameter D .

By the use of equations (1) and (4), a waveguide taper having a length of 208 inches (approximately $17\frac{1}{2}$ feet) comprising 12 conical sections with half-taper angles from $1^\circ 23.5'$ to $7^\circ 44.2'$ is obtained. The dimensions of 12 taper sections comprising my waveguide taper device are as follows.

	Inside diameter range, inches	Length, inches	Half taper angle	Wall thickness, inches
Section:				
3a	2.250-4.600	11.50	$7^\circ 44.2'$	0.100
3b	4.600-9.926	19.602	$7^\circ 44.2'$	3/16
3c	9.926-15.100	19.050	$7^\circ 44.2'$	0.250
4a	15.100-17.750	15.145	5°	0.032
4b	17.750-20.400	15.145	5°	0.032
5a	20.400-22.250	17.750	$2^\circ 59'$	0.032
5b	22.250-24.100	17.750	$2^\circ 59'$	0.032
5c	24.100-25.950	17.750	$2^\circ 59'$	0.040
6a	25.950-26.887	19.307	$1^\circ 23.5'$	0.040
6b	26.887-27.825	19.307	$1^\circ 23.5'$	0.040
6c	27.825-28.762	19.307	$1^\circ 23.5'$	0.040
6d	28.762-29.700	19.307	$1^\circ 23.5'$	0.040

The junctions 9, 10, 11 and 12 generate substantially identical amplitudes of the $TE_{0,2}^o$ mode and the differential phase difference between adjacent junctions is 90° . The two pairs of junctions 9, 10 and 11, 12 are interlaced such that the first and third junctions (9, 11) are π radians apart in terms of the beat wavelength of the $TE_{0,1}^o$ and $TE_{0,2}^o$ modes, and the second and fourth junctions (10, 12) are also π radians apart and staggered 90° from the first pair. This interlacing or cascading results in the first and third mode converting junctions cancelling as a pair thereby minimizing $TE_{0,1}^o$ and $TE_{0,2}^o$ mode of conversions (i.e., minimizing the loss of power to the $TE_{0,2}^o$ mode and maximizing the desired $TE_{0,1}^o$ mode of propagation) and also resulting in a minimum length of waveguide taper. Although the phase of the second pair of junctions 10, 12, is a quadrature (i.e. 90° staggered to that of the first pair, this feature is not essential since the mode cancellation is achieved by pairs of junctions.

Cover flanges 13 are utilized to connect adjacent conical sections together, and such flanges are fastened on the ends of the conical sections by any convenient means such as bonding, or the use of epoxy. Circular stiffening rings 14 are employed on the outer conical surfaces for assuring circularity of the respective conical sections. The number of stiffening rings utilized with each section is determined by the tolerances defined for the waveguide taper. As an example, one stiffening ring was used with section 4a, and the surface thereof was true to within ± 0.005 inch in circularity and straightness relative to a perfect cone.

The nine larger diameter conical sections (from 4a to 6b) thin wall members and are fabricated by the longitudinal welding of rolled aluminum sheet metal. The smallest diameter conical section 3a provides a continuously variable taper angle to blend into the 2.25-inch diameter input waveguide, and this blend has a radius of approximately 24 inches. The constant flare angle produced by the continuously variable taper angle prevents the generation of any higher order modes and thus the junction of section 3 and the input waveguide 7 is not considered to a mode conversion junction. Section 3a is electroformed whereas the other thicker wall sections 3b and 3c are machined. The specific 12-section waveguide taper hereinabove described has been tested and found to meet the various specifications hereinabove described including that of low fabrications costs, light weight and acceptable electrical characteristics including that of negligible mode conversion losses as measured by a spinning dipole mode analyzer technique whereby the greatly oversize circular waveguide 8 is capable of the transmission of microwave power several orders of magnitude above that of conventional waveguides. Thus, the waveguide taper hereinabove described is compatible with the low loss transmission line produced by the oversize waveguide. In particular, in my specific 208-inch length taper the strongest higher order modes detected, the $TE_{0,2}^o$, $TE_{0,3}^o$ and $TE_{0,21}^o$ modes, are weaker than 20 db. below the $TE_{0,1}^o$ mode. The length dimensions of the four subdivided sections 3, 4, 5, 6 are indicated on FIG. 1. The largest diameter section 6d, and its flanged connection to the oversize circular waveguide 8 is illustrated in FIG. 2.

The waveguide taper is fabricated by the following method. The smallest diameter section 3a is fabricated by employing an electroforming process and the next sections 3b and 3c are

fabricated by machining (boring) raw aluminum stock. The nine larger diameter sections are fabricated by rolling thin aluminum sheet metal (0.032 and 0.040-inch thickness) into the desired conical shapes and longitudinal butt-welding of such thin-wall sections 4a to 6d. A special arc-welding fixture was built for obtaining the longitudinal welds. Successful longitudinal welds produced by the relatively low-cost special arc-welding fixture are limited to approximately 24 inches in length, since the thin aluminum sheet metal must be welded under very carefully controlled conditions in order to obtain conical sections having the desired preciseness in circularity of cross section. It is this welding limitation which limits the maximum axial length of each taper section. Obviously, longer length sections can be produced by employing higher cost welding fixtures, but this would then negate one of the objects of my invention, that of providing a low-cost fabrication method.

After the conical sections have been welded, the stiffening rings are slid onto desired axial locations of the various sections. As indicated in FIG. 1, one stiffening ring 14 is used on small diameter sections 3b, 3c, 4a, 4b, 5a, 5b, 5c, and two stiffening rings are used on large diameter sections 6a, 6b, 6c, 6d. The stiffening rings are approximately equally spaced from each other and from the section ends. After the stiffening rings are in place, the cover flanges 13 are slid onto the ends of each section. A special epoxying fixture is utilized for fastening the flanges and stiffening rings onto the waveguide taper sections. The epoxying fixture is used to align the flanges and stiffening rings on the taper section, and after alignment, epoxy, is used to bond the flanges and rings onto each taper section.

After the conical sections have been completely fabricated, they are assembled into a single structure. A long support structure is utilized for aligning the 12 conical sections, and for holding and aligning the 17.5 foot long taper with the oversize circular waveguide and input waveguide. The support structure is diagonally braced for increased rigidity and is bolted to the ground for stability. An optical technique is used in the alignment process including a pinpoint diameter light source fastened one-half inch radially outward on a flange at one end of the waveguide assembly and a pinpoint diameter peep hole similarly fastened outward on a flange at the other end thereof. An 8 inch long tapered piece of metal made from sheet aluminum having ends three-eighths inch and five-eighths inch wide, respectively, is placed on each intervening flange, and by noting the position of the taper that would decrease by one-half the light seen through the peep hole, the position of the largest diameter flange interconnecting the taper and oversize waveguide is determined.

An average optical axis was established that permits flange alignment to within the range of the adjusting screws on leveling fixtures located on top of the support structure. The flanges interconnecting sections 5b, 5c and 6a of the waveguide taper are then bolted together and aligned with the average optical axis. Thereafter, the alignment of the remaining sections is adjusted by the leveling fixtures to make the mating flanges parallel after which the flanges are bolted together. In the final assembly, all of the flanges were aligned within $\pm 3/64$ inch and $\pm 3/128$ inch the horizontal and vertical planes, respectively.

From the foregoing description, it can be appreciated that my invention make available an improved minimum length waveguide taper device and low-cost method of fabrication thereof. The particular 17.5 foot length is a substantial reduction in length from a 30 foot continuously variable taper which exhibits comparable electrical characteristics. The waveguide taper is adapted for interconnecting waveguides of substantially different diameter sizes, and in particular, is especially adapted for interconnecting a small diameter input waveguide to a greatly oversize circular waveguide suitable for transmitting power levels at X-band frequencies of several orders of magnitude higher than that of conventional size waveguides. The waveguide taper may also find application as a broadband radiating element or radiating aperture having

negligible phase and amplitude distortion. Although the particular waveguide taper described hereinabove may be fabricated by other means, the other methods are all inherently much more expensive thereby rendering it economically unfeasible for use of such component in a microwave system for transmitting bulk power. The use of a plurality of reinforced thin-walled waveguide taper sections results in a low-cost fabrication method which provides the desired dimensions and tolerances and obtains acceptable electrical characteristics including those of negligible mode conversion and the further advantage of being lightweight.

Having described the waveguide taper structure and method of fabrication in accordance with my invention, it is believed obvious that other modifications and variations of my invention are possible in the light of the above teachings. For example, a more expensive welding jig can be utilized for welding seams greater than 24 inches in length and thereby utilizing a smaller number than 12 for the sections comprising my 17.5 foot length taper. Further, the stiffening rings may be omitted by utilizing thicker walls in the waveguide taper sections. However, these modifications result in either or both a more expensive fabrications method and structure and also a greater weight structure. Thus, since one of the objects of the invention is to provide a low-cost, lightweight structure, it is seen that the use of a plurality of short length, reinforced, thin-walled conical sections is the preferred embodiment. My invention is thus defined by the following claims.

I claim:

1. A waveguide taper of minimum length for interconnecting two circular waveguides differing substantially in diameter size comprising:

12 conical waveguide sections connected in order of increasing diameters, said sections having selected axial lengths and four different taper angles for minimizing the generation of spurious modes at the junctions of different taper angles, the larger diameter conical sections comprising thin-wall members;

pairs of alternate junctions being interlaced and the junctions of each pair being π radians apart in terms of the beat wavelength of a dominant and spurious mode of propagation to thereby substantially cancel the effect of the spurious mode and provide a waveguide taper of length substantially shorter than a waveguide taper having a continuously variable taper wherein both waveguide tapers are adapted for propagating the same dominant mode at the same frequency and having comparable electrical characteristics; and

the four sections of largest diameter have a first common taper angle, the next three sections have a second common taper angle, the next two sections have a third common taper angle, and the three smallest diameter sections have a fourth common taper angle.

2. The waveguide taper of minimum length set forth in claim 1 wherein the smallest diameter section has a continuously variable taper angle terminating in the fourth common taper angle whereby four junctions of different taper angles are provided to form two interlaced pairs of the alternate junctions.

3. The waveguide taper of minimum length set forth in claim 2 wherein:

said waveguide taper has minimum and maximum inside diameters of 2.250 and 29.700 inches, respectively; and said waveguide taper has a total length of 208 inches which is substantially shorter than a comparable continuously variable taper having similar electrical characteristics and a minimum total length of 30 feet wherein the waveguide tapers are adapted for propagating the TE_{01} mode at X-band frequency with negligible mode conversion losses.

4. The waveguide taper of minimum length set forth in claim 3 wherein the first common taper is $1^\circ 23.5'$, the second common taper angle is $2^\circ 59'$, the third common taper angle is 5° , and the fourth common taper angle is $7^\circ 44.2'$.

5. The waveguide taper minimum length set forth in claim 4

wherein the four sections of largest diameter each have an axial length of 19.307 inches, the next three sections each have an axial length of 17.750 inches, and the next two sections each have an axial length of 15.145 inches.

6. The waveguide taper of minimum length set forth in claim 5 wherein the five sections of largest diameter each have a wall thickness of 0.040 inch and the next four sections each have a wall thickness of 0.032 inch.

7. A waveguide taper of minimum length for interconnecting two circular waveguides differing substantially in diameter size comprising:

12 conical waveguide sections connected in order of increasing diameters, said sections having selected axial lengths and four different taper angles for minimizing the

generation of spurious modes at the junctions of different taper angles, the larger diameter conical sections comprising thin-wall members; and
pairs of alternate junctions being interlaced and the junctions of each pair being π radians apart in terms of the beat wavelength of a dominant and spurious mode of propagation to thereby substantially cancel the effects of the spurious mode and provide a waveguide taper of length substantially shorter than a waveguide taper having a continuously variable taper wherein both waveguide tapers are adapted for propagating the same dominant mode at the same frequency and having comparable electrical characteristics.

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