AD-A164 726 MINIMIZING EHF WAVEGUIDE LOSSES(U) ROME AIR DEVELOPMENT CENTER GRIFFISS AFB NY E W GILBERTSON DEC 85 RADC-TR-85-223 1/1

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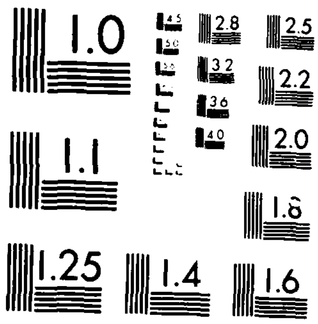

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AD-A164 726

RADC-TR-85-223
In-House Report
December 1985

MINIMIZING EHF WAVEGUIDE LOSSES

Edward W. Gilbertson, Captain, USAF

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ADA 164 726

REPORT DOCUMENTATION PAGE

1a REPORT SECURITY CLASSIFICATION: UNCLASSIFIED	1b RESTRICTIVE MARKINGS: N/A
2a SECURITY CLASSIFICATION AUTHORITY: N/A	3 DISTRIBUTION / AVAILABILITY OF REPORT: Approved for public release; distribution unlimited
2b DECLASSIFICATION / DOWNGRADING SCHEDULE: N/A	
4 PERFORMING ORGANIZATION REPORT NUMBER(S): RADC-TR-85-223	5 MONITORING ORGANIZATION REPORT NUMBER(S): N/A
6a NAME OF PERFORMING ORGANIZATION: Rome Air Development Center; 6b OFFICE SYMBOL (If applicable): DCCR	7a NAME OF MONITORING ORGANIZATION: N/A
6c ADDRESS (City, State, and ZIP Code): Griffiss AFB NY 13441-5700	7b ADDRESS (City, State, and ZIP Code): N/A
8a NAME OF FUNDING / SPONSORING ORGANIZATION: Rome Air Development Center; 8b OFFICE SYMBOL (If applicable): DCCR	9 PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER: N/A
8c ADDRESS (City, State, and ZIP Code): Griffiss AFB NY 13441-5700	10 SOURCE OF FUNDING NUMBERS: PROGRAM ELEMENT NO 63431F; PROJECT NO 1227; TASK NO 00; WORK UNIT ACCESSION NO 03

11 TITLE (Include Security Classification)
MINIMIZING EHF WAVEGUIDE LOSSES

12 PERSONAL AUTHOR(S)
Edward W. Gilbertson, Capt, USAF

13a TYPE OF REPORT	13b TIME COVERED	14 DATE OF REPORT (Year, Month, Day)	15 PAGE COUNT
In-House	FROM ____ TO ____	December 1985	84

16 SUPPLEMENTARY NOTATION
N/A

17 COSATI CODES			18 SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB GROUP	
09	01		Waveguide; EHF; Dielectric Waveguide; Oversized Waveguide; Overmoded Waveguide; Circular Waveguide; Attenuation

19 ABSTRACT (Continue on reverse if necessary and identify by block number)

To minimize RF power transmission losses at high frequencies, rectangular waveguide has become the standard transmission medium. At EHF frequencies, rectangular waveguide attenuation rises to unacceptably high levels. To minimize waveguide loss, length is minimized. Where this is not possible, a variety of alternatives exist, each having lower attenuation than standard rectangular waveguide and each with its own advantages and limitations. Square circular (modes TE_{11} and TE_{01}), oversized rectangular, oversized circular (modes TE_{11} and TE_{01}), and dielectric waveguides are addressed and categorized according to bendability. By choosing the technology with the lowest attenuation which meets the installation's bendability requirements, the optimum transmission method can be determined. Attenuations are calculated for comparison at 44 GHz, but the discussion is general enough to hold throughout the EHF frequency range.

20 DISTRIBUTION / AVAILABILITY OF ABSTRACT	21 ABSTRACT SECURITY CLASSIFICATION
☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS	UNCLASSIFIED

22a NAME OF RESPONSIBLE INDIVIDUAL	22b TELEPHONE (Include Area Code)	22c OFFICE SYMBOL
Edward W. Gilbertson, Capt, USAF	(315) 330-3091	RADC (DCCR)

DD FORM 1473, 84 MAR — 83 APR edition may be used until exhausted. All other editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE
UNCLASSIFIED

ACKNOWLEDGEMENTS

I would like to acknowledge the help and cooperation of fellow RADC engineers, Lincoln Lab engineers, Naval engineers of NUSC, NESEA, NOSC, and the Norfolk Naval Shipyard/Combat Systems Office. I would also like to acknowledge the assistance provided by the countless contractor representatives and engineers contacted. I would particularly like to acknowledge the help of Mr. Mike Devan of the Naval Ocean Systems Center, who has provided me with much of the information presented here and many points of contact.

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INTRODUCTION & SCOPE

1.1 INTRODUCTION

Assume that, for a particular system, both the transmitter and the antenna(s) have been chosen and that for some reason, the two cannot be collocated. The next decision is how to interconnect them. At UHF and some SHF frequencies, coaxial cable is standard. At some SHF and all EHF frequencies, rectangular waveguide is standard.

Rectangular waveguide losses increase as the frequency range of the waveguide increases. By EHF frequencies, the waveguide losses which were negligible at lower frequencies are now formidable. At 44 GHz, waveguide losses are 0.25 dB per foot or half power every 12 feet. The foregone conclusion to use rectangular waveguide should be reexamined for each system employing a long run (5 ft or more) of EHF rectangular waveguide.

Specifically, given a particular EHF system, what transmission methods offer the lowest attenuation but can still satisfy the environmental and bendability requirements of a given installation. There are several alternatives available which have lower loss than standard rectangular waveguide. Some of these are not bendable, some can only make rigid bends, while still others can be either semirigid or flexible. No matter what your installation physically requires, lower losses than standard rectangular waveguide can be realized if the length of the run exceeds a certain threshold distance (4 ft for 44 GHz).

1.2 SCOPE

Dealing completely with minimizing losses in waveguide at EHF frequencies could easily fill several volumes. This paper is directed toward examining alternatives for a 10 to 100W transmitter installed aboard an aircraft with its antenna(s) located less than 25 ft away. The attenuation figures shown have been calculated based upon a frequency of 44 GHz. Bends are probably a necessity. Semi-rigid sections are a real world need caused by the requirement to install manufactured waveguide sections into aircraft which vary somewhat from airframe to airframe. Flexible sections may be useful to reduce the stress on the waveguide as the aircraft flexes.

In order of importance, the criteria for comparing transmission techniques are attenuation, rigid bendability, semi-rigid bendability, and flexibility. Of these four criteria, the first is desired to be as low as possible, but the remaining three will be dictated by the particular aircraft installation. Although these criteria are examined in terms of a 44 GHz installation under 25 ft in length, the transmission methods discussed are the alternatives available throughout the EHF frequency range for almost any transmission distance.

SECTION 2

WAVEGUIDES - GENERAL

There are an infinite number of modes possible in waveguides. Modes are designated by the shape of the waveguide in which they propagate and by either a TE_{xx} or a TM_{xx} designation. Transverse Electric (TE_{xx}) waveguide modes are also designated as H_{xx}, while Transverse Magnetic (TM_{xx}) modes are also E_{xx} modes. The xx subscripts refer to the electromagnetic patterns within the waveguides as the mode propagates energy through the guide.

Waveguides generally have one intended or desired or primary mode of propagation. This mode transfers the energy. Undesirable modes are any modes whose existence cause a noticeable decrease in the energy of the desired mode. They either excessively lose energy in transmission through the guide or are generated at the expense of energy from the desired mode and are of a form not recoverable by the transition at the receiving end. Either way, they are lost energy in transmission and appear as an increase in waveguide attenuation.

A waveguide will propagate a mode if the guide is large enough. Another way of looking at this is that any mode will propagate in a waveguide if the mode's cut off frequency (fc) is below the frequency being propagated. In this way, waveguides act as high pass filters, passing only those frequencies above fc. The waveguide's cut off is extremely sharp, however, since at fc and below, the attenuation is infinite while at frequencies just 1.15 times fc, the waveguide is a usable transmission medium (see Table 1). Since the cutoff frequency, fc, is a direct function

Mode	Rectangular TE_{10}	Circular TE_{11}	Circular TE_{01}
Cutoff Frequency, f_c (GHz)	$\frac{5.902}{a}$ a is H plane dimension in inches	$\frac{6.917}{a}$ a is diameter in inches	$\frac{14.40}{a}$ a is diameter in inches
Normal Operating Frequency Range	1.25 f_c to 1.88 f_c	1.15 f_c to 1.58 f_c (1.15 TE_{11} to 0.95 TE_{21} f_c)	1.21 f_c to 1.66 f_c (1.21 TE_{01} f_c to .91 TE_{02} f_c)

TABLE 1: Cutoff and Operating Frequencies of Waveguides

of the waveguide's size, waveguide sizing is very important.

Waveguide sizes are generally chosen so that undesirable modes propagate at or near their cutoff frequencies while the desired mode propagates well above its fc. In this way, undesired modes are greatly attenuated while the desired mode propagates with relatively low attenuation. Standard sized waveguides, therefore, have a mode filtering effect and can often be used without a separate mode filter.

The larger the waveguide the lower its attenuation. However, as the waveguide is made larger, the waveguide's sensitivity to imperfections and the number of higher ordered modes which are able to propagate increases. Propagation through a perfectly straight, perfectly smooth, and either perfectly rectangular or perfectly circular waveguide would achieve the theoretical attenuation of Table 1. Imperfections, however, convert a fraction of the energy from the desired mode into any other propagation modes which are possible in the guide. When the desired mode is transitioned back out of the guide at the receiving end, undesireable modes appear as increased waveguide attenuation because they do not transition out of the guide and are lost energy.

These waveguide imperfections introduce inductive or capacitive components into the guide's attenuation. As the guide's attenuation becomes lower, these reactive components have a greater and greater effect. Impedance mismatches, the generation of higher ordered undesireable modes, resulting high VSWR's, and high attenuation are all effects. This can be likened to a tuned circuit. Two reactive components separated by a low impedance connection can form a resonant circuit with a high Q. Adding attenuation in series helps to dampen this high Q resonant circuit and decrease the magnitude of any resonant oscillations generated. In low attenuation waveguide, this dampening of the waveguide "Q" for undesirable modes may be done by adding mode filters in series with the waveguide or by properly sizing the waveguide. Either of these techniques selectively attenuates the undesirable propagation modes while passing the desired mode. Another possible way to reduce the resonance Q is to decrease the magnitude of the reactances, themselves. By eliminating bends from the waveguide, the reactances will be reduced.

Reference Table Of Rigid Rectangular Waveguide And Flanges

EIA WG WR ( ) MDL Band	Recommended Operating Range for TE 10 Mode: Frequency GHz	Wavelength (cm)	Cut-off for TE 10 Mode: Frequency GHz	Wavelength (cm)	Range in $\frac{2\lambda}{\lambda c}$	Range in $\frac{\lambda g}{\lambda}$	Theoretical cw power rating lowest to highest frequency (mw)	Theoretical Attenuation lowest to highest frequency (dB/100 ft)	EIA WG WR ( )	JAN WG RG ( )	Material Alloy	JAN FLANGE: Choke UG ( )/U	Cover UG ( )/U	DIMENSIONS (Inches): Inside	Tol ±	Outside	Tol ±	Wall Thickness (nom)
340	2.20-3.30	13.63-9.08	1.736	17.27	1.58-1.05	1.78-1.22	3.1-4.5	.877-.572 .751-.492	340	112 113	Brass Alum		553 554	3.400-1.700	0.005	3.560-1.860	.005	0.080
284 S	2.60-3.95	11.53-7.59	2.078	14.43	1.60-1.05	1.67-1.17	2.2-3.2	1.102-.752 .940-.641	284	48 75	Brass Alum	54B 585A	53 584	2.840-1.340	0.005	3.000-1.500	.005	0.080
229	3.30-4.90	9.08-6.12	2.577	11.63	1.56-1.05	1.62-1.17	1.6-2.2		229					2.290-1.145	0.005	2.418-1.273	.005	0.064
187 C	3.95-5.85	7.59-5.12	3.152	9.510	1.60-1.08	1.67-1.19	1.4-2.0	2.08-1.44 1.77-1.12	187	49 95	Brass Alum	148C 406B	149A 407	1.872-0.872	0.005	2.000-1.000	.005	0.064
159	4.90-7.05	6.12-4.25	3.711	8.078	1.51-1.05	1.52-1.19	0.79-1.0		159					1.590-0.795	0.004	1.718-0.923	.004	0.064
137	5.85-8.20	5.12-3.66	4.301	6.970	1.47-1.05	1.48-1.17	0.56-0.71	2.87-2.30 2.45-1.94	137	50 106	Brass Alum	343B 440B	344 441	1.372-0.622	0.004	1.500-0.750	.004	0.064
112 X_L	7.05-10.0	4.25-2.99	5.259	5.700	1.49-1.05	1.51-1.17	0.35-0.46	2.12-3.21 2.50-2.74	112	54 68	Brass Alum	52B 137B	51 138	1.122-0.497	0.004	1.250-0.625	.004	0.064
102	7.05-10.0								102	320	Brass	1494	1493	1.020-0.510	0.003	1.148-0.638	.003	0.064
90 X	8.20-12.40	3.66-2.42	6.557	4.572	1.60-1.06	1.68-1.18	0.20-0.29	6.45-4.48 5.49-3.83	90	52 67	Brass Alum	40B 136B	39 135	0.900-0.400	0.003	1.000-0.500	0.003	0.050
75	10.00-15.00	2.99-2.00	7.868	3.810	1.57-1.05	1.64-1.17	0.17-0.23		75					0.750-0.375	0.003	0.850-0.475	0.003	0.050
62 Ku	12.4-18.0	2.42-1.66	9.486	3.160	1.53-1.05	1.55-1.18	0.12-0.16	9.51-8.31 6.14-5.36	62	91 107	Brass Alum Silver	541A — —	419 — —	0.622-0.311	0.002	0.702-0.391	0.003	0.040
51	15.00-22.00	2.00-1.36	11.574	2.590	1.54-1.05	1.58-1.18	0.080-0.107		51					0.510-0.255	0.0025	0.590-0.335	0.003	0.040
42 K	18.00-26.50	1.66-1.13	14.047	2.134	1.56-1.06	1.60-1.18	0.043-0.058	20.7-14.8 17.6-12.6 13.3-9.5	42	53 121 66	Brass Alum Silver	596A 598A	595 597	0.420-0.170	0.0020	0.500-0.250	0.003	0.040
34	22.00-33.00	1.36-0.91	17.328	1.730	1.57-1.05	1.62-1.18	0.034-0.048		34		Brass		1530	0.340-0.170	0.0020	0.420-0.250	0.003	0.040
28 K_A	26.50-40.00	1.13-0.75	21.081	1.422	1.59-1.05	1.65-1.17	0.022-0.031	21.9-15.0	28	96	Brass Alum Silver	600A — —	599 — —	0.280-0.140	0.0015	0.360-0.220	0.002	0.040
22 Q	33.00-50.00	0.91-0.60	26.342	1.138	1.60-1.05	1.67-1.17	0.014-0.020	31.0-20.9	22	97	Brass Silver		383	0.224-0.112	0.0010	0.304-0.192	0.002	0.040
19	40.00-60.00	0.75-0.50	31.357	0.956	1.57-1.05	1.63-1.16	0.011-0.015		19		Brass		529	0.188-0.094	0.0010	0.268-0.174	0.002	0.040
15 V	50.00-75.00	0.60-0.40	39.863	0.752	1.60-1.06	1.67-1.17	0.0063-0.0090	52.9-39.1	15	98	Brass Silver		385	0.148-0.074	0.0010	0.228-0.154	0.002	0.040
12	60.00-90.00	0.50-0.33	48.350	0.620	1.61-1.06	1.68-1.18	0.0042-0.0060	93.3-52.2	12	99	Brass Silver		387	0.122-0.061	0.0005	0.202-0.141	0.002	0.040
10 W	75.00-110.0	0.40-0.27	59.010	0.508	1.57-1.06	1.61-1.18	0.0030-0.0041		10		Brass		1528	0.100-0.050	0.0005	0.180-0.130	0.002	0.040

Table 2: Standard Rectangular Waveguide

TECHNOLOGY	ATTENUATION	FURTHER CONSIDERATION
Microstrip, Finline, Stripline, etc.	$\leq$ 4 dB/ft	DELETE
Coaxial Cables		
Flexible/Semirigid	1.7 dB/ft	DELETE
Helical	(Not above 20 GHz)	DELETE
Superconducting	0.5 dB/ft	DELETE
Dielectric Waveguide	0.12 - 1.5 dB/ft	YES
Waveguide		
Dielectric Filled	0.5 dB/ft	DELETE
WR22	0.229 dB/ft	YES
Square	0.15 dB/ft	YES
Elliptical	(Not above 20 GHz)	DELETE
Circular	0.03 - 0.1 dB/ft	YES
Oversized Rectangular	0.03 dB/ft	YES
Oversized Circular	0.0005 - 0.001 dB/ft	YES

TABLE 3: ATTENUATIONS OF AVAILABLE TECHNOLOGIES.

SECTION 3

ATTENUATION, THE PRIMARY CRITERION

Attenuation is the primary criterion. Since rectangular waveguide exists, is easily available, and works reliably at EHF frequencies, the technologies we consider must perform better than standard rectangular waveguide. Table 2 shows a portion of a standard rectangular waveguide table. 44 GHz transmission utilizes WR 22 waveguide with an attenuation of 0.23 dB per foot (theoretical). Actual high conductivity copper waveguide will measure about 15 % higher than theoretical or about 0.26 dB per foot at 44 GHz. By eliminating all transmission technologies which cannot achieve attenuations less than 0.26 dB per foot, we can make standard rectangular waveguide performance the acceptance standard. This narrows the field under consideration as shown in Table 3 to circular waveguide, square waveguide, oversized waveguide (both circular and rectangular), and dielectric waveguide. These will be addressed in turn, but first I would like to address several of the deleted technologies.

Several of the technologies deleted in Table 3 are self-explanatory. Microstrip, finline, and stripline are integrated circuit techniques which are far too lossy when scaled up from micro to macro scale. Coaxial cables are too lossy above 40 GHz and some, such as helical cables, are not made above 20 GHz. Likewise, elliptical waveguide is not manufactured for use above 20 GHz either.

Dielectric filled waveguide is basically a waveguide which has been filled with a dielectric material. It's losses must be greater than the losses of an unfilled waveguide because waveguide attenuation is the sum of conductive waveguide losses and bulk dielectric losses. The bulk dielectric losses must increase when filling the waveguide with any dielectric material. In addition, filling the waveguide with dielectric must cause the size of the waveguide to decrease because of the slowing of electromagnetic propagation within the guide caused by the dielectric. This decrease in waveguide size causes a corresponding increase in the conductive losses in the guide, so both the dielectric bulk losses and conductive losses will increase when dielectric filling is added. The only advantage to filling a waveguide with a dielectric is in increasing its power handling capacity. Since none of the technologies of interest which remain from Table 3 are limited by their power handling capacity, for our purposes, dielectric filling offers us no advantages.

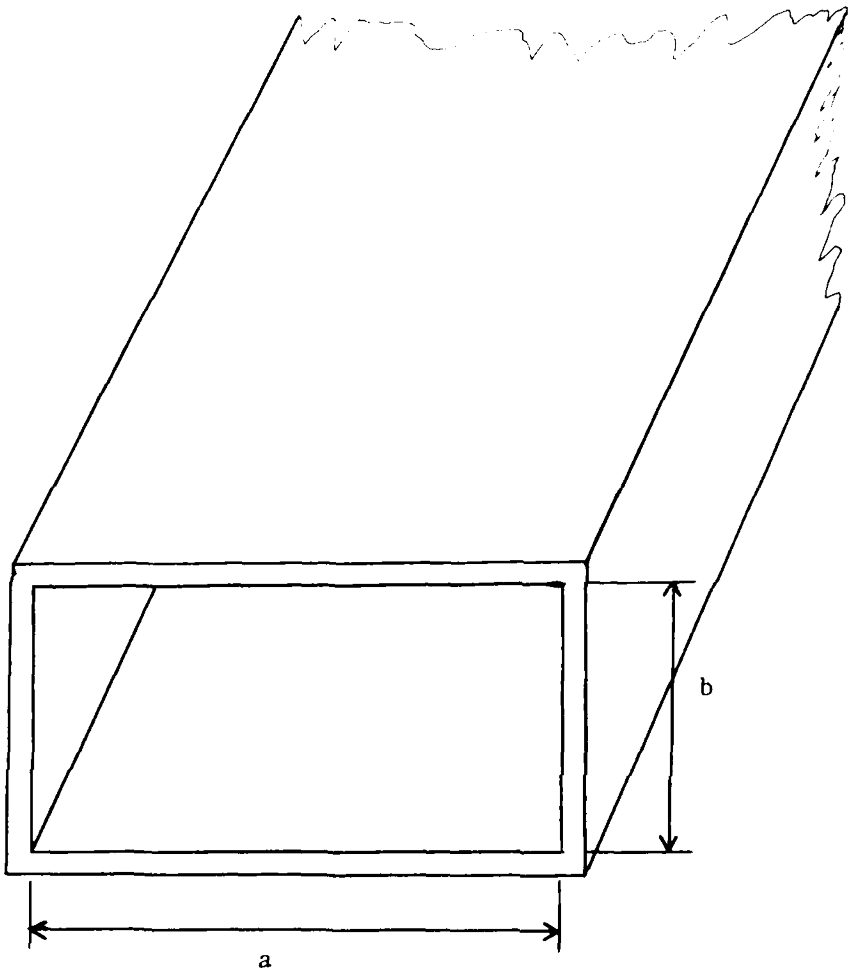
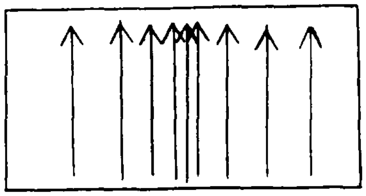
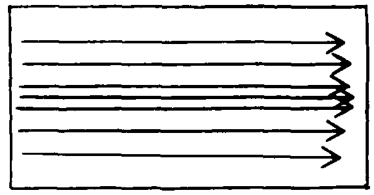


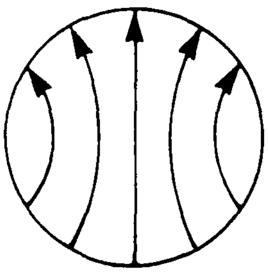
Figure 1: Rectangular Waveguide Cross Section & Axes



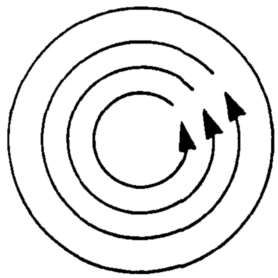
Rectangular TE_{10} Mode



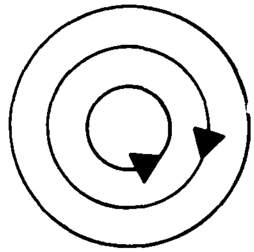
Rectangular TE_{01} Mode



Circular TE_{11} Mode

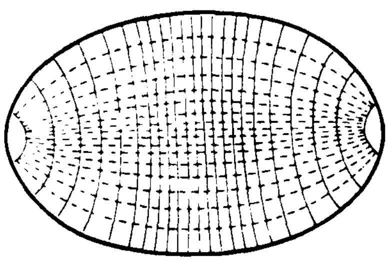


Circular TE_{01} Mode
("Low Loss Mode")

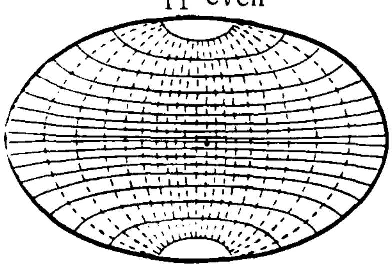


Circular TE_{02} Mode

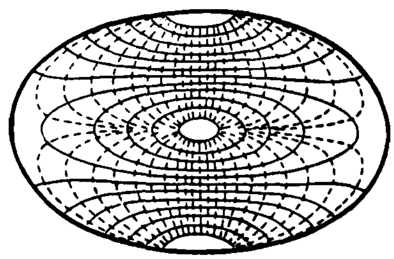
DISTORTIONS CAUSED BY ELLIPTICITIES IN CIRCULAR GUIDES



TE_{11} even



TE_{11} odd



TE_{01} even

Figure 2: E-Field Patterns of Waveguide Modes

SECTION 4

THE TECHNOLOGIES

4.1 RECTANGULAR WAVEGUIDE - THE STANDARD

The standard way to connect EHF and even most SHF equipment is to use rectangular waveguide. Coaxial cable is also an alternative (especially at SHF frequencies), but when low transmission line loss or high power transmission are required, the use of coaxial cable becomes unsatisfactory. At SHF frequencies, waveguide is practically without attenuation, but as communications frequencies increase into the EHF range, even the comparatively low attenuation of rectangular waveguide becomes formidable.

Table 2 shows some standard rectangular waveguide sizes and characteristics. There are almost 30 standard sizes with frequency ranges distributed between 750 MHz to 325 GHz. For 44 GHz operation, the stand rd sized waveguide is designated WR 22. The shape and axes of standard waveguide are as shown in Figure 1 with the ratio of a:b being 2:1. This ratio determines the operating bandwidth of the waveguide. Energy is propagated through rectangular waveguide using the rectangular Transverse Electric (TE) mode TE_{10} which is shown in Figure 2.

Attenuation in any waveguide is dependent upon the conductivity of the metal forming the interior surface of the waveguide. This conductivity of metal is not necessarily the same as the conductivity of metals found in most tables of electrical conductivity. Most tables show values for electrical conductivity which are measured using direct current (d.c.). Waveguides are operated at frequencies measuring in the GHz. At these

Material	Eff. cond. σ at λ = 1.25 cm in 10^7 mhos/m	DC cond. σ in 10^7 mhos/m
Aluminum:†		
Pure, commercial (machined surface)	1.97	3.25 (measured)
17S Alloy† (machined surface)	1.19	1.95 (measured)
24S Alloy (machined surface)	1.54	1.66 (measured)
Brass:		
Yellow (80-20) drawn waveguide	1.45	1.57 (measured)
Red (85-15) drawn waveguide	2.22	
Yellow round drawn tubing	1.36	1.56 (Eshbach)
Yellow (80-20) (machined surface)	1.17	1.57 (Eshbach)
Free machining brass (machine surface)	1.11	1.48 (measured)
Cadmium plate	1.04–0.89	1.33 *Hdbk. of Phys. and Chem.*
Chromium plate, dull	1.49–0.99	3.84 *Hdbk. of Phys. and Chem.*
Copper:		
Drawn OFC waveguide	4.00	5.48 (measured)
Drawn round tubing	4.10	4.50 (measured)
Machined surface†	4.65	5.50 (measured)
Copper plate	2.28–1.81	5.92 } *Hdbk. of Phys. and Chem.*
Electroformed waveguide†	3.15	5.92 } *Hdbk. of Phys. and Chem.*
Gold plate	1.87	4.10 *Hdbk. of Phys. and Chem.*
Silver:		
Coin silver drawn waveguide	3.33	4.79 (measured)
Coin silver lined waveguide	1.87 }	4.79 (assumed)
Coin silver (machined surface)†	2.66 }	4.79 (assumed)
Fine silver (machined surface)†	2.92 }	6.14 *Hdbk. of Phys. and Chem.*
Silver plate	3.98–2.05 }	6.14 *Hdbk. of Phys. and Chem.*
Solder, soft†	0.600	0.70 (measured)

Table 4: Conductivity of metals at 24 GHz Abstracted from N. Marcuvitz, "Waveguide Handbook" MIT Radiation Laboratory Series, Copyright 1951.

frequencies the conductivity of metal can vary substantially from d.c. measured values as shown by Table 4. Table 4 illustrates that the lowest loss waveguide interior lining would be copper (as measured at 24 GHz). Coin silver is often used as a substitute for copper because of its somewhat better resistance to corrosion. The oxide of silver is electrically conductive, unlike most oxides. However, as Table 4 suggests, lower attenuation can be achieved by using a copper waveguide. Some corrosion resistance for copper waveguide can be obtained by using a conformal coating such as Alodine or Iridite.

Since WR 22 is the standard "transmission line" for use at 44 GHz, its performance is the yardstick against which other technologies must be judged. If made of high conductivity copper, straight sections of WR 22 have an attenuation of 0.26 dB per foot. Each 90° rigid waveguide bend adds approximately 0.15 dB to this attenuation; each flange interface adds about half as much, or 0.07 dB. Straight sections of waveguide are available in continuous lengths of up to 20 feet. Several commercial bending houses can form custom bends or shapes in straight waveguide sections to manufacture custom waveguide sections for unique installation requirements. The minimum rigid waveguide bend radius is less than ½ inch. Flexible sections of WR 22 are available from Technicraft, a division of Tech Systems Corp. The lengths of these short, flexible sections have a maximum length of 2¼ inches and their attenuation is about 0.6 dB per foot or 0.05 dB per inch.

Rectangular waveguide interfaces are easy to define and are the standard interfaces between EHF units. Interfaces between laboratory power sources, detectors, couplers, mixers, combiners, attenuators, terminations, etc.; at EHF frequencies are in terms of rectangular waveguide. The inputs and outputs of EHF equipment use rectangular waveguide. Any alternative waveguide or transmission line must be able to be converted from rectangular waveguide at its beginning and back to rectangular waveguide at its end. At any points where measurements must be taken, conversion to rectangular waveguide must again take place.

4.2 CIRCULAR WAVEGUIDE

In general, circular waveguide has lower attenuation than rectangular waveguide, but is more difficlt to work with. The attenuations of the two commonly used modes in circular waveguide, TE_{11} and TE_{01}, are one third and one tenth, respectively, of the attenuations in corresponding rectangular waveguides. Figure 3 helps to show the very real advantages circular waveguide can offer in reducing attenuation. Circular waveguide is more difficult to work with than rectangular waveguide primarily because it is more difficult to bend. Bending a waveguide with a circular cross section tends to produce a waveguide having an elliptical cross section. Ellipticities in circular waveguide, like any other waveguide irregularity, increase the guide's attenuation. In addition, because of the lower attenuation of circular waveguide, the effect of waveguide irregularities of any sort is more pronounced. The main differences between the two commonly used circular waveguide modes can be summarized that the TE_{11} mode behaves much more like rectangular waveguide than does the TE_{01} mode. The TE_{11} mode, if sized small enough, can make bends almost as tight as standard rectangular waveguide. The TE_{01} mode, on the other hand, has a minimum bend radius of about 18 inches unless special techniques are used

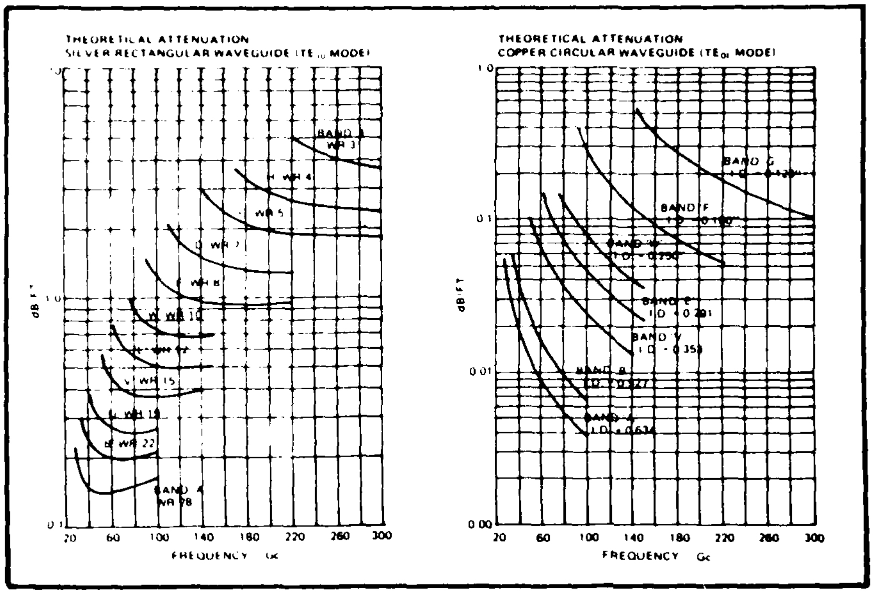


Figure 3: Theoretical Attenuations of Rectangular TE_{10} and TE_{01} Modes (electroformed, internally corrugated bends).

The TE_{11} mode is the dominant mode of circular waveguide just like the TE_{10} mode is the dominant mode of rectangular waveguide. These two dominant modes can be launched in their waveguides using simple probe launchers, while the circular TE_{01} mode requires a more complicated mode launcher. The rectangular TE_{10} and the circular TE_{11} modes, like most other modes, decrease their attenuation as frequency increases only up to a certain point, beyond which their attenuation begins to increase again. This is not true of the circular TE_{01} mode. It's attenuation decreases infinitely as frequency increases infinitely.

TE_{mn} MODES

n \ m	0	1	2	3	4	5	6	7
1	2.081	1	1.659	2.282	2.888	3.485	4.074	4.659
2	3.811	2.896	3.643	4.354	5.042	5.714	6.374	7.024
3	5.526	4.637	5.415	6.163	6.889	7.598		
4	7.237	6.359	7.154					

TM_{mn} MODES

n \ m	0	1	2	3	4	5	6	7
1	1.306	2.081	2.790	3.466	4.122	4.764	5.397	6.022
2	2.998	3.811	4.572	5.302	6.010	6.702	7.381	8.051
3	4.701	5.526	6.312	7.070	7.807			
4	6.405	7.237	8.037					

Example: If a circular waveguide has a TE_{11} mode cutoff frequency of 10 GHz, the same diameter guide has a TE_{01} cutoff at 20.81 GHz, a TM_{01} cutoff at 13.06 GHz, etc.

Example: (These ratios are also the ratios of diameters of waveguides operating at the same cutoff frequency in different modes). At 17.57 GHz mode TE_{11} is at its cutoff frequency in a 1 cm diameter waveguide. Mode TM_{02} cuts off at 17.57 GHz in a 2.998 cm diameter waveguide, etc.

TABLE 5: RELATIVE CUTOFF FREQUENCIES FOR CIRCULAR WAVEGUIDE MODES (NORMALIZED TO CIRCULAR TE_{11} MODE).

4.2.1 TE_{11} MODE

4.2.1.1 Mode TE_{11} Discussion

Of the two primary circular waveguide modes, TE_{11} is the most commonly used. It is also the dominant mode of circular waveguide. This means that the TE_{11} mode can propagate in a waveguide which is too small for any other modes (See Table 5). Another way of looking at the dominant mode is that it's F_c is lower than that of any other mode for a given circular waveguide diameter. Being the dominant mode offers the advantage that, if properly sized, a waveguide can filter out all other modes and keep the transmission pure TE_{11} mode. The TE_{11} mode is, therefore, not as sensitive to attenuation caused by bending as the TE_{01} mode is. In its ability to be bent, TE_{11} mode circular waveguide behaves much more like rectangular waveguide and can be bent tightly if the waveguide is made with a small diameter. Standard TE_{11} waveguide is designed large enough to propagate the TE_{11} mode but too small to allow the TE_{01} mode (See Table 1). The circular TM_{01} mode cutoff is in between these two and it's presence is generally tolerated. TM_{01} mode oscillations, if generated, dampen out because their attenuation is much higher than mode TE_{11}. Mode TE_{11} waveguide is sized as large as possible (approaching the TE_{01} mode cutoff size as closely as can be tolerated) because this achieves the lowest attenuation while still retaining the waveguide's ability to be bent.

To achieve the tightest radius of bend possible in the TE_{11} mode, the waveguide size should be decreased to a point where only the TE_{11} mode and not the TM_{01} mode is permitted to propagate. This smaller than normal TE_{11} mode waveguide will have a higher attenuation than normal TE_{11} waveguide, but can make bends as tightly as WR22. At 44 GHz, the diameter waveguide where mode TM_{01} is cutoff is 0.205 in. The mode TE_{11} diameter for a cutoff frequency of 44 GHz is 0.157 in. The minimum sized waveguide which would normally be used for mode TE_{11} at 44 GHz is 0.18 in. diameter guide (See Table 1). Any size waveguide having between 0.18 in. and 0.205 in. diameter would allow minimal radius bends in TE_{11} mode at 44 GHz. The smaller diameters allow propagation of a wider bandwidth signal.

The two main considerations in using circular TE_{11} mode are to use large radius bends and to keep transitions, mode filters, etc., aligned; since the TE_{11} mode is linearly polarized, by launching two linearly polarized TE_{11} signals at right angles to one another (orthogonal propagation) two separate signals could theoretically be transmitted down the same waveguide. At high frequencies, orthomode transducers are only used to feed antennas with separate horizontally polarized and vertically polarized components. At lower frequencies (13 GHz or below) the orthomode technique is sometimes used to feed one transmission line with two separable signals. Unfiltered lower frequency waveguides achieve signal separations of 30dB whereas filtering can double or triple that figure. Surface irregularities and waveguide irregularities degrade the signal separation as a linear function of waveguide length.

The second problem with TE_{11} mode waveguide is maintaining a circular cross section. Elliptical cross sections distort the original TE_{11} signal and convert portions of its energy into even and odd TE_{11} functions. These functions are linearly polarized along the major and minor axes of the waveguide's ellipticity (See Figure 2). Controllable in straight sections, ellipticities become a problem in bends. Instead of energy arriving at the output transition aligned with the plane of the output transition, it arrives with some combination of alignments. The improperly aligned energy is lost and appears as increased attenuation.

Overall, the TE_{11} mode is an easily implemented way to reduce waveguide losses below those of rectangular waveguides. The components are commercially available from many manufacturers. Extreme care is not necessary in using the TE_{11} mode and its use should be considered.

4.2.1.2 Mode TE_{11} Components

4.2.1.2.1 Component Availability

TE_{11} mode components have long been used in antenna feeds and in rotary joints so they are readily available in frequencies through 110 GHz. The following list is by no means complete nor it it meant to be a recommendation of any particular manufacturer. It's purpose is only to show that a variety of mode TE_{11} components are commercially available and require no development costs prior to their use. A few manufacturers are:

Straight sections - Alpha, Azdar (A division of the British EVERED Company), and many tubing mills

Precision straight sections - Azdar, and many tubing mills

Bends - may be made in-house or by commercial waveguide benders

Transitions/transducers (TE_{11} to rectangular TE_{10}) - Alpha Hughes, *Microwave Research Corp.*, Systron Donner, Flann Microwave

Transitions (circular to circular) - Alpha

RIGID CIRCULAR WAVEGUIDE

Type designation	Frequency Range (GHz)		Dimension (inches)					
	TE_{01} mode	TE_{11} mode	Inside Diameter	Inside Tolerance (±)	Outside Diameter	Outside Tolerance (±)	Nominal Wall Thickness	Max I.D. Out of Round
WRC454D14	9 950 13 700	4 540 6 230	1 750	0 0015	2 010	0 004	0 130	0 004
WRC530D14	11 600 16 000	5 300 7 270	1 500	0 0015	1 7[illegible]	0 003	0 100	0 004
WRC621D14	13 000 18 700	6 210 3 510	1.281	0 0015	1 441	0 003	0 080	0 004
WRC727D14	15 900 21 900	7 270 9 970	1 094	0 0013	1 224	0 003	0 065	0 004
WRC849D14	18.600 25 600	8 490 11 600	0 938	0 0013	1 068	0 003	0 065	0 004
WRC997D14	21 900 30 100	9 970 13 700	0 797	0 0013	0 897	0 0025	0 050	0 003
WRC116C14	25 300 34 900	11 600- 15 900	0 688	0 0013	0 788	0 0025	0 050	0 003
WRC134C14	29 300 40 400	13 400 18 400	0 594	0 001	0 674	0 0025	0 040	0 003
WRC159C14	34 800- 48 000	15 900- 21 800	0 500	0 001	0 580	0 002	0 040	0 003
WRC182C14	39 800- 54 800	18 200 24 900	0 438	0 001	0 518	0 002	0 040	0 003
WRC212C14	46 400 63 900	21 200- 29 100	0 375	0 001	0 435	0 002	0 030	0 003
WRC243C14	53 100- 73 100	24 300 33 200	0 328	0 001	0 388	0 002	0.030	0 002
WRC283C14	61 900- 85 200	28 300- 38 800	0 281	0 001	0 341	0 002	0 030	0 002
WRC318C14	69 700- 95 900	31 800 43 600	0 250	0 001	0 290	0 002	0 020	0 002
WRC364C14	79 600 110.000	36 400 49 800	0 219	0 001	0 259	0 002	0 020	0 002
WRC424C14	92 900-128 000	42 400 58 100	0 188	0 001	0 228	0 002	0 020	0 002
WRC463C14	101 000 139 000	46 300 63 500	0 172	0 001	0 212	0 002	0 020	0 002
WRC566C14	124 000-171 000	56 000- 77 500	0 141	0 001	0 181	0 002	0 020	0 002
WRC635C14	139 000 192 000	63 500- 87 200	0 125	0 001	0 155	0.002	0 015	0 002
WRC727C14	159 000-219 000	72 700- 99 700	0 109	0 001	0 139	0 002	0 015	0 002
WRC848C14	186 000-256 000	84 800-116.000	0 094	0.001	0 124	0 002	0 015	0.002

Table 6: Circular Waveguide Sizes

Orthomode transitions/transducers - Alpha, Hughes

Circular Polarizers - Alpha, Hughes, Microwave Research Corp., Systron Donner

TE_{11} Rotary Joints - most rotary joint manufacturers

Terminations (sliding or fixed) - Microwave Research Corp.

4.2.1.2.2 Component Descriptions

Standard Straight Sections (See Table 6) - standard waveguide sections for mode TE_{11} at 44 GHz have an internal diameter of 0.24 in. or less with a dimensional tolerance of +/-0.001 in. For minimum attenuation, copper waveguide should be used at EHF frequencies because of its higher conductivity than silver (See Table 4). If necessary, a conformal coating may be added for corrosion resistance as was described for standard rectangular waveguide already.

Precision Straight Sections - These have the same internal diameter as standard straight sections, but the dimensional tolerances are better than +/-0.0001 in for 44 GHz.

Bends - Mode TE_{11} behaves very much like standard rectangular waveguide in bends. Normal waveguide bending techniques may be used successfully for most bends; but, for tight bends (under 4 - 6 in radius) a waveguide diameter of between TE_{11} cutoff (0.157 in) and mode TM_{01} cutoff (.21 in) should be used.

Transitions (TE_{11} to rectangular TE_{10}) - Transitions are also called transducers since they convert energy from one propagation mode to another. A smooth geometric transition from a rectangular to a circular cross section converts TE_{11} to rectangular TE_{10} mode. The same transition may also be used to convert rectangular mode TE_{10} into circular TE_{11} mode. The loss for a single transition from one mode to the other at 44 GHz is 0.1 dB. For a waveguide run with a transition at either end the total transition losses would, therefore, be 0.2 dB.

Transitions (circular to circular) - These are merely a linearly tapered transition from one size of circular waveguide to another. Since they do not convert energy from one mode to another, they are not referred to as transducers. Transitions could be used in transitioning from a series of tight bends to a straight section of larger diameter and vice versa.

Orthomode transitions/transducers - Orthomode transducers take two rectangular mode TE_{10} inputs/outputs and join them together in a single circular mode TE_{11} waveguide. Separations of greater than 30 dB can be obtained at frequencies up to 170 GHz. Since long lengths of circular waveguide degrade the signal separations, orthomode transducers are normally used only immediately prior to an antenna feed.

Circular polarizers - Polarizers may be switchable either electrically or mechanically or they may be fixed. The fixed polarizers convert a linearly polarized signal to a right hand or left hand circularly polarized signal. They may also convert backwards from either left or right hand circular polarization to linear polarization. Mechanically switchable polarizers can convert a linearly polarized signal to RHCP, LHCP, or may leave it linearly polarized. Some mechanically switchable polarizers (Alpha) can convert horizontal linear polarization to vertical linear polarization and vice versa. Electrically controlled polarization switches are available (Alpha) which can rotate linear polarization continuously +/-

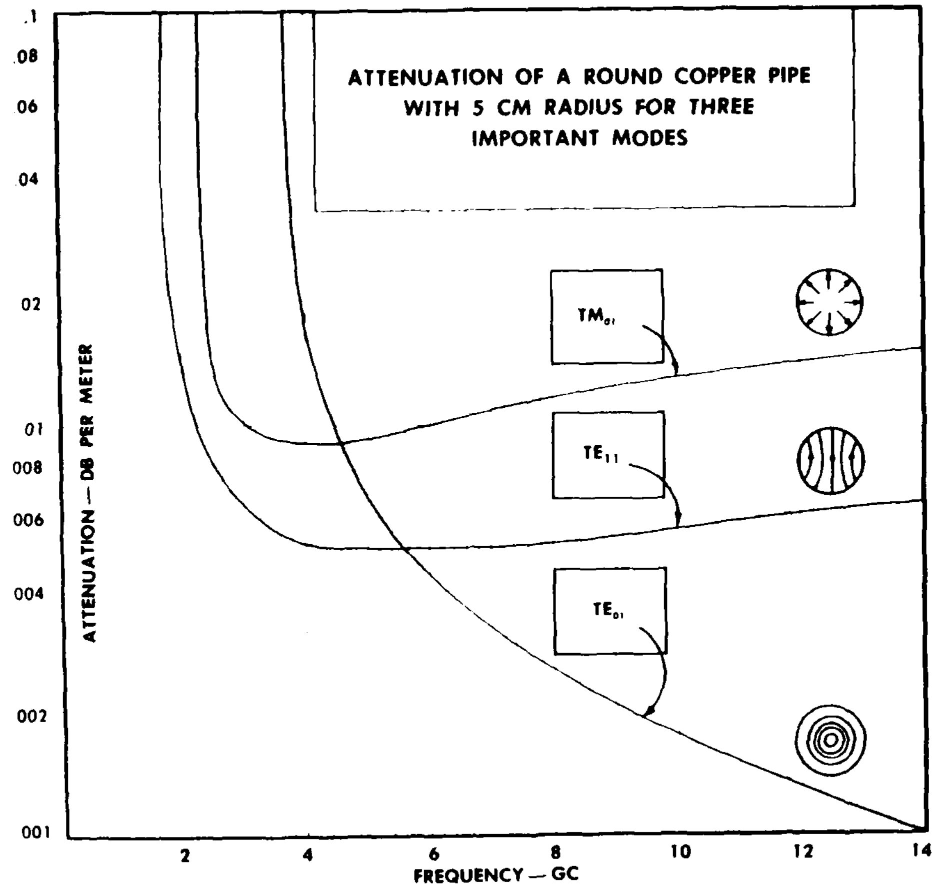


Figure 4: Attenuation of Various Modes in 10cm Copper Circular Waveguide

From: "The Microwave Engineers' Handbook and Buyers' Guide", Horizon House, Copyright 1966

(Reprinted by permission from MICROWAVE ENGINEERING HANDBOOK & BUYERS GUIDE, 1966)

135^{o} within 10 w sec.

Rotary Joints - Provided a circular polarizer is used at each end of a circular waveguide, a rotary joint in circular waveguide is fairly easy to implement.

Terminations - Terminations are made in the same way as for any other waveguide termination. A tapered piece of lossy absorber material is placed inside a section of waveguide. The taper of the absorber is different for different modes.

4.2.2 TE_{01} Mode, the "Low Loss" Mode

4.2.2.1 Mode TE_{01} Discussion

Of all waveguide modes, the circular TE_{01} mode has the potential to have the lowest attenuation. Most waveguide modes decrease in attenuation as frequency increases up to a certain frequency. Beyond that point, most waveguide modes increase attenuation as frequency increases. The circular TE_{01} mode decreases in attenuation infinitely as frequency increases infinitely (Illustrated in Figure 4). It is because of this characteristic that the circular TE_{01} mode has been nicknamed the "Low Loss" mode. In actuality, this characteristic is not peculiar to only the circular TE_{01} mode, but is also possessed by all of its higher ordered relatives, the circular TE_{0n} modes. Nonetheless, it is only the TE_{01} mode which has been dubbed "Low Loss".

The "Low Loss" mode has two other unusual characteristics. First, it has no longitudinal wall currents. All electrical currents in the waveguide wall travel circumferentially around the waveguide, none longitudinally along its length. Second, those wall currents which do exist are extremely small. The TE_{01} mode has no electrical field lines which terminate at the waveguide's surface (See Figure 2), therefore, there are theoretically no surface currents in the guide. TE_{01} waveguides may, therefore, be made of aluminum rather than high conductivity copper with little degradation in performance. Also, because there are no longitudinal currents, electrical contact between the circular waveguide sections is not an absolute requirement. Flange losses are, therefore, lower and rotary joints are made much easier, almost trivial. It is also because of these peculiar characteristics of the TE_{01} mode that mode filters and sharp bends can be made simply.

The TE_{01} mode has an attenuation much lower than rectangular waveguide. It is one third that of the TE_{11} mode or about one tenth that of standard rectangular waveguide for the same frequency range (See Figure 3).

This low attenuation is not gained without a complication, however. This waveguide is much more sensitive to the introduction of reactances than is either the circular TE_{11} or rectangular TE_{10} waveguide. (Reactances and their causes were discussed in the section on TE_{11} waveguide.) This sensitivity to reactances limits the minimum radius TE_{01} waveguide bend at 33 GHz to about an 18 inch radius of bend. If a bend is made tighter than that, the VSWR will rise above 1.07 (see the section on bends to follow). There are techniques for making TE_{01} bends with smaller radii than 18 inches, but these will also be discussed in the pages to follow, section on TE_{01} bends.

The TE_{01} mode has lower loss per foot than the TE_{11} , but it's losses transitioning into or out of the mode are higher. Each TE_{01} transition loses only 0.2 to 0.3 dB, whereas each TE_{11} transition loses only 0.1 dB going to or from rectangular waveguide at 44 GHz. Because of these higher transition losses, components such as terminations and directional couplers find more use in TE_{01} (Low Loss) mode than in TE_{11} mode. In the TE_{11} mode, it is nearly as effective to transition to rectangular waveguide and either terminate the signal or measure the mode's power.

The standard size for circular waveguide operating in the TE_{01} mode is the largest diameter possible without allowing propagation of the TE_{02} mode. This size allows the propagation of 13 other modes (see Table 5). Because of the many extraneous possible propagation modes, the TE_{01} mode waveguide is more sensitive than the TE_{11} mode to waveguide irregularities or bends. Luckily, all of these other modes propagate using longitudinal surface currents and can be selectively attenuated without attenuating the TE_{01} mode strongly. The TE_{02} mode does not contain longitudinal currents and conventional TE_{01} mode filters do not attenuate it.

4.2.2.2 Mode TE_{01} Components

4.2.2.2.1 Component Availability

TE_{01} components are not as readily available as are TE_{11} mode components. As communication frequencies have reached EHF frequencies only recently, and since waveguide losses were acceptable up until this time, the number of distributers is still limited. Several individuals or small organizations have developed their own designs for their own uses or for profit. The following list is by no means all inclusive nor should it be misconstrued as a recommendation of one manufacturer over another. This list is mainly meant to show system designers, who are thinking of using mode TE_{01}, that some hardware does exist and is available which requires little, if any, development.

Straight sections - Alpha, Azdar, and many tubing mills. Some tubing mills such as Uniform Tubes Inc. & A.T. Wall have no minimum charge and will handle small orders. Most tubing mills require a 1000 lb minimum order.

Precision Straight sections - Azdar and many tubing mills.

Bends - There are two methods of making bends:

(a) Conventionally bending the waveguide.

(b) Making a waveguide section which is internally corrugated.

Conventional waveguide bends - No waveguide manufacturer or waveguide bender at present will guarantee the results of any TE_{01} waveguide sections which they bend to shape. (Some will bend with no guarantees.) However, bends may be made in-house by filling the waveguide before bending and by keeping the radius of bend greater than 18 inches.

Internally Corrugated Waveguide Bends - These must be electroformed to maintain the tight tolerances required. Many electroformers will produce these bends including A.J. Tuck, Gamma F of CA, and Servometer.

Transitions/Transducers (TE_{01} to rectangular TE_{10})

(a) Iris transitions - Alpha TRG

(b) Marie' transitions - Mr. Tor Anderson of Antennas for Communication Corp., who works closely with A.J. Tuck, Inc. of Connecticut has a design. Harris Corp also has a design. Both have been manufactured, tested and work well. Most electroformers such as A.J. Tuck or Gamma F. can electroform the transitions. Marconi stocks marie' transitions up to 40 GHz.

Transitions (Circular to Circular) - Alpha

TE_{01} Rotary Joints - Alpha, most rotary joint manufacturers, Harris may have a marketable version of their design.

Terminations - Alpha.

Directional couplers - NOSC has a design coupling circular Q-band circular waveguide into WR22 rectangular waveguide.

4.2.2.2.2 Component Descriptions

Straight Waveguide Sections - Straight waveguide sections and precision straight waveguide sections are identical to those used for circular mode TE_{11}. Because of the low wall currents of the low loss mode, aluminum or another metal with a lower conductivity than copper or silver is satisfactory for use. Copper and silver waveguide is more readily available, however, being used already for the TE_{11} mode.

Bends-low lossses in TE_{01} circular waveguides depend on the waveguide being circular. If the waveguide becomes elliptical, other modes are generated and attenuation increases. Bending a circular pipe produces an elliptical cross section by nature. In order to keep the cross section a circle, extreme care must be taken in bending. Large radius bends with a small (90^{o} or less) angle of bend can be made by conventional bending techniques (filling the guide with sand or Serrobend, bending, and then removing the filling). To make tight radius bends, a technique of electroforming internally corrugated, bendable waveguide sections has been developed. These techniques will be discussed separately.

The Navy SPN42 automatic carrier landing system experienced some difficulties with making waveguide bends. It used some circular low loss mode at 33.2 GHz in waveguide with an internal diameter of 0.688 in. Some installations required bends in the guide, but no manufacturer would guarantee a successful product. The unguaranteed bends which were produced were unsuccessful and had unacceptable VSWR's of 1.6 to 1.8. So the Navy had their personnel at the Norfolk Naval Shipyard combat systems office try to make some bends in-house. Results were much better. BY filling the waveguide with sand or a wax-like material prior to bending the guide, acceptable VSWR's of 1.07 or less could be achieved on 18" radius 45° bends. Besides the one 45° bend, six 30° bends were successfully made with 18" radii using this technique. However, successful small (under 18") radius bends cannot be made by this technique.

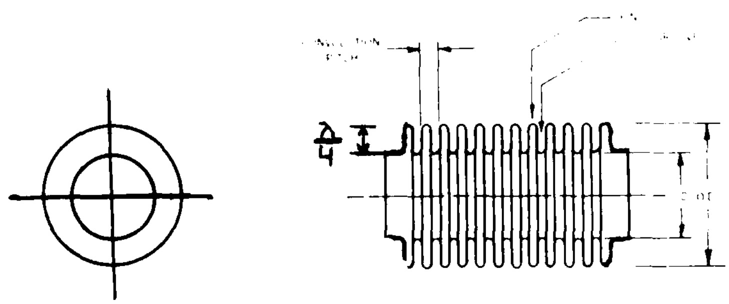


Figure 5: Internally corrugated electroformed bend for "Low Loss" mode

The best method for making small radius bends in circular waveguide is to use electroformed internally corrugated waveguide sections. The TE_{01} mode has no longitudinal wall currents, only circumferential ones. By cutting circumferential grooves into the inside waveguide surface, the waveguide is divided into a series of connected rings. Surface currents may flow circumferentially not longitudinally, thus suppressing the generation of any extraneous modes. In addition, these circular corrugations perform in a truss-like manner to preserve the circular cross section of the waveguide when the waveguide is bent. For best effect, the corrugations should be made one quarter wavelength deep so as to appear like an infinite impedance to longitudinally propagating surface currents (a quarter wavelength stub ending in a short). There should be at least four corrugations per waveguide wavelength or else their effect diminishes according to NOSC unpublished test results.

The best technique for producing these corrugated bends is to electroform straight sections on a mandrel, dissolve the mandrel, and then bend the straight sections to the desired curve. A new mandrel must be machined for each bend. Depending on the materials used to electroplate the mandrel and their thickness, the corrugated bend may be either rigid, semi-rigid, or flexible. Semi-rigid bends may be formed by electroforming copper on an aluminum mandrel, dissolving the mandrel, and nickel plating the copper guide. By using non-work hardening metals like nickel, flexible bends can be made. The interior surface of a bend may be electroplated with silver or copper for better conductivity. NOSC measurements on actual bends show a 0.2 to 0.25 dB loss through an 8 inch section at 45.5 GHz with a bandwidth of 2 GHz. Bandwidths of corrugated waveguide bends are limited to about 2 GHz at 45 GHz. This limitation is caused by the limited effective frequency range of the quarter wavelength corrugations. Threading the interior of circular waveguide rather than electroforming has been tried by NRL but results were unpredictable and low yields were experienced.

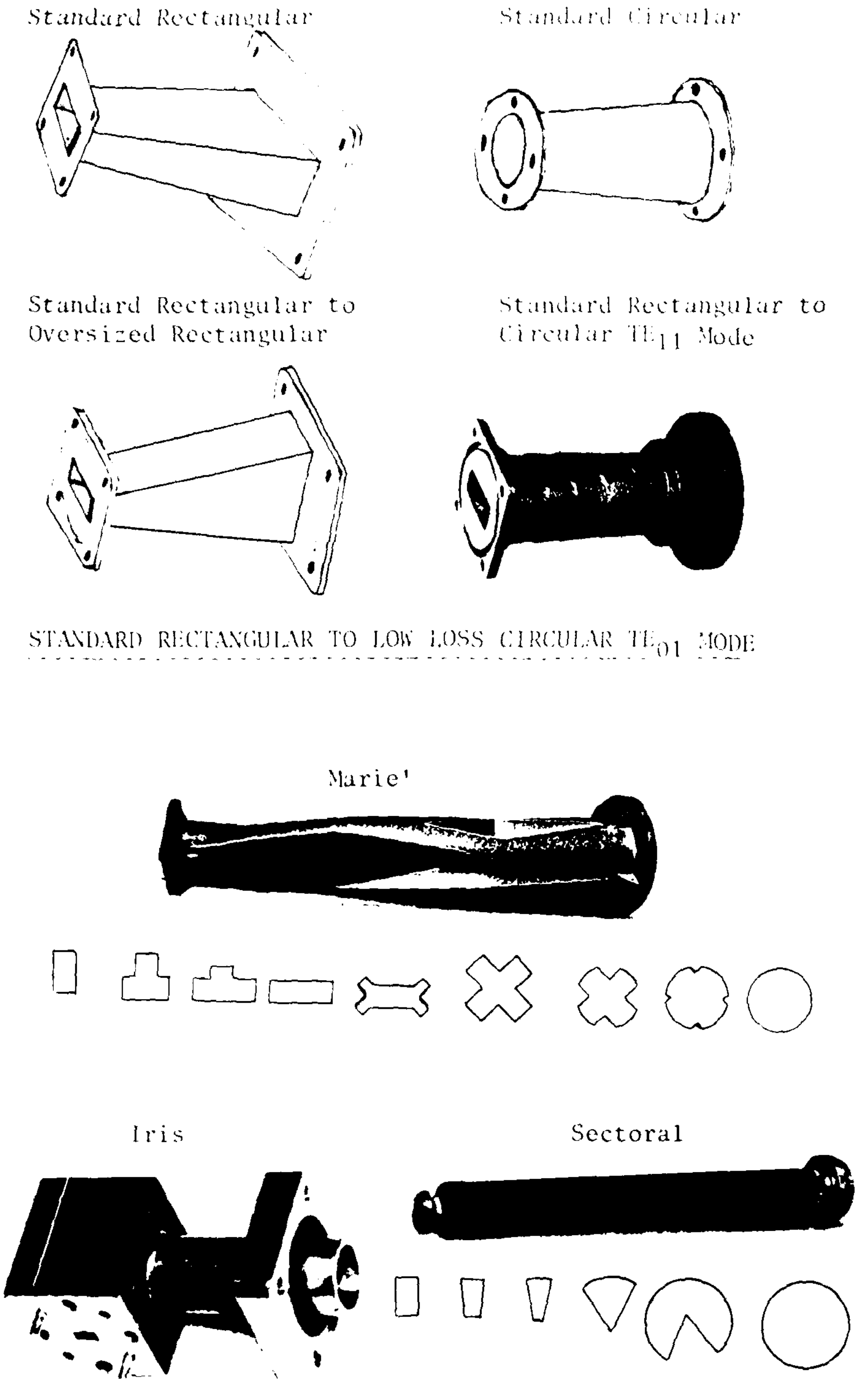


Figure 6: Waveguide Transitions

Mode Filters - The simplicity of TE_{01} mode filters is one of the chief reasons why the low loss mode is so easy to work with. The same techniques used to make corrugated bends can be used to make effective mode filters. Circumferentially grooved circular waveguide attenuates all modes except the TE_{0n} modes. In a mode filter, the grooves between the ridges internal to the waveguide are filled with a lossy energy absorber. The absorber accentuates the mode filtering effect of the grooves. Like internally corrugated waveguide bends, this mode filter design must be electroformed.

An alternate, but similar, approach to mode filter design employs a wound helical wire form surrounded by energy absorber material. Like internal corrugations, the spaces between the coils of the helix prevent longitudinal current flow allowing only circumferential currents. Commercially available, this design works nearly as well as the electroformed type and is cheaper to manufacture. Manufacturer's literature for this design quotes a maximum insertion loss of 0.2 dB for TE_{01} propagation from 33 to 50 GHz.

Transitions/Transducers - There are three types of low loss mode transitions: the sectoral, which is no longer commercially available; the iris, which is commercially available; and the marie', which is commercially available but has only been designed, manufactured, and tested in limited quantities for higher frequencies. (See Figure 6)

The sectoral transition geometrically transitions from a rectangular to a circular waveguide. First, one narrow wall of the rectangular waveguide is reduced in width until the waveguide's cross section becomes triangular. (See Figure 6) Next, the triangular guide gradually widens its arc until it forms a circular waveguide with a narrow wall in it.

Lastly, this wall is decreased in size to leave a circular waveguide. The TE_{01} mode emerges along the same axis as the original TE_{10} mode which entered the transition. Being a geometric transition, the sectoral can have a broad bandwidth. Sectoral transitions were manufactured by Hitachi, but their circular waveguide line was discontinued when sold to Hughes. There is no advantage to redeveloping this transition since the marie' has the same characteristics.

The iris transition is a narrow band device with its bandwidth limited to about 6%. In this transition, the narrow wall of a standard rectangular waveguide is separated by a thin septum, forming two parallel, thin waveguide sections. An iris is cut in one of the narrow walls and a circularly oriented E-field is used to transition between modes TE_{10} and TE_{01}. Thus the output of an iris transition emerges at right angles to the input. The iris transition is a very reactive device: say for example, if two transitions are separated by a short length of circular waveguide, mode filters may be required. The same may be true if a transition is followed too closely by a waveguide bend or other reactive device. Unless reactive effects become involved, iris transitions will perform almost as well as marie' transitions with iris losses being 0.25 to 0.3 dB per transition.

Marie' transitions, like sectoral transitions, use a geometric design and are broad band devices. The transition to the low loss mode is performed in three stages. (See Figure 6) First, the TE_{10} rectangular mode is transitioned to TE_{20} rectangular mode. By attaching the narrow wall of the TE_{10} rectangular waveguide at right angles to the broad wall of a piece of waveguide which is twice as long, the TE_{20} rectangular mode is generated in the wider waveguide. This overly wide waveguide is then split at each end to form a "dog-bone" shaped cross section for the guide. This splitting at each end continues until an X-shaped cross section is formed. This X-shape is then gradually thickened to leave only the circular waveguide remaining. If properly designed and manufactured, the impedance of a marie' transition is purely resistive, therefore, mode filters do not become necessary unless other reactive devices are involved. Insertion losses are 0.2 to 0.25 dB per transition and as with the sectoral type, the output energy is collinear with the input energy. Harris has recently manufactured Marie' transitions with only 0.1 dB loss.

Rotary Joints - Single channel rotary joints are simple with the TE_{01} mode. Because of the lack of longitudinal currents, electrical contact between the two sliding waveguide interfaces is not essential. High power transmission with losses can be easily achieved. If a second channel is desired, however, another mode must be used because orthomode transducers do not exist for the TE_{01} mode, which do not affect any energy already present in a circular waveguide.

Terminations - Terminations are commercially available and are easily formed. A conical piece of absorber material placed in the end of a truncated section of circular waveguide does the trick nicely (with VSWR's of 1.05 or less).

Directional Couplers - Since WR22 is the standard interface for instrumentation at 44 GHz, a directional coupler which samples a small portion of the signal in a circular waveguide and has an output in rectangular waveguide is useful for monitoring active systems. Although there are no commercially available units that I have found which sample TE_{01} mode, NOSC has an excellent design for a 20 dB directional coupler.

This design has a coupling of approximately 20 dB into WR22 waveguide with an isolation of 34 dB. It can simultaneously couple forward and reflected (reverse) power so that readings of transmit power and calculations of VSWR can be made in operating circuits.

4.2.2.2.3 Operational Experience

Bell Laboratories researched a great deal of what we know today about mode TE_{01} during the 1950's and 1960's. Their research was directed towards developing a low attenuation method of transferring extremely wide bandwidths for several miles. This was related to the picture phone concept which required extremely wide bandwidths to be feasible. When research in fiber optics began, Bell's research of oversized low loss mode waveguide stopped. Much of their work has been published in the Bell Systems Technical Journal. (See Appendix 2) The Japanese used oversized, over moded TE_{01} mode waveguide underground. Nippon Electric used oversized circular guide to transmit telecommunications for several miles underneath city streets. Most of their circular waveguide equipment such as mode filters were made by Hitachi. Nippon Electric replaced their circular waveguides with fiber optics. Hitachi sold their waveguide manufacturing to Hughes who discontinued production of the circular components due to low demand.

The best example of operational experience with standard sized low loss mode circular waveguide is the Navy SPN42 System. The SPN42 is an automatic carrier landing system which operates at 33.2 GHz. On some aircraft carriers (such as the Midway) waveguide runs from the transmitter to the antenna can be as long as 20 ft. These long runs are necessitated by the transmitter's need to be sheltered from the weather while the antenna must be located high on the tower and exposed. Although originally implemented 19 years ago using rectangular waveguide, some of the carriers were modified to use circular TE_{01} mode waveguide around 1977-78. Only those carriers with waveguide runs exceeding 15 feet from transmitter output to antenna pedestal were modified to use circular TE_{01}.

Coin silver rectangular RG96 waveguide (WR28) was replaced by WRC116C14 (0.688 in internal diameter) circular waveguide on runs generally 15-18 feet in length. Iris transitions were used along with mode filters after each transition. Total loss for the circular waveguide run was specified to be less than 2.0 dB from transmitter output to antenna pedestal. These specifications were achieved and there was no increase in maintenance caused by the use of circular waveguide instead of rectangular. This is according to the Naval Electronics Systems Engineering Activity (NESEA) which monitors, tests, and certifies modifications or repairs to the SPN 42 System.

This is not meant to imply that the SPN 42 circular waveguide was used without problems. Besides the difficulty of bending low loss mode waveguide (which was discussed in the section on TE_{01} mode bends), the main problem which the SPN 42 System waveguide suffered from was the growth of green fungus within the guide. This occurred with either rectangular or circular waveguide and was related to the environmental exposure of the guide and not to the type of guide used.

Lead times on the SPN 42 circular waveguide components were considered to be long by the Norfolk repair personnel. The Oxygen Free High Conductivity (OFHC) copper circular waveguide had a lead time of 8-10 months. Silver waveguide averaged about a month longer. To retard corrosion of the copper guide conformal coatings were applied. The coatings used were either Alodine or Iridite depending on whether a conductive or insulative coating was required. These coatings were applied at Norfolk so their lead time was negligible. Lead times for the iris transitions and the mode filters could be up to a maximum of 150 days.

The new version of the SPN 42 system no longer requires the use of long runs of waveguide. The SPN 46 system collocates the transmitter and the antenna pedestal. The need to use circular waveguide no longer exists with this new system.

4.3 OVERSIZED WAVEGUIDES

Generally, the attenuation of a waveguide decreases somewhat linearly as the surface area or circumference increases. The obvious question is, therefore, "Why not use a very large waveguide and achieve a very low attenuation?". This is precisely the principle behind oversized or overmoded waveguides.

There are limits on how large a waveguide can be oversized before its attenuation begins to increase rather than decrease. In addition, oversized waveguides cannot be bent. In spite of these restrictions, oversized waveguide offers the lowest attenuation for long waveguide runs and its use should be examined.

As a waveguide's size increases, the number of modes which can propagate through it increases dramatically. An oversized waveguide is a waveguide which allows many modes other than the desired mode to propagate, some of which cannot be filtered separately from the desired mode. For rectangular TE_{10} mode waveguide, oversized means any size larger than the minimum to propagate the TE_{20} mode. For the circular TE_{01} Low Loss mode waveguide, it is any size larger than the minimum to propagate the circular TE_{02} mode. For circular TE_{11} mode, it is any size large enough to propagate the low loss mode.

The large number of modes which can propagate through the waveguide makes oversized waveguide extremely sensitive to surface irregularities or bends. As is the case with standard sized circular waveguide, bends or irregularities tend to couple energy from the desired mode into undesired modes which must then be filtered out. Since filtering cannot eliminate all unwanted modes, and since the impedance of the waveguide to the many unwanted modes is extremely low, an unacceptably high percentage of power is lost by bending oversized waveguide. Therefore, oversized waveguide cannot be bent. Surface irregularities or imperfections lose power also. Using precision waveguide reduces these losses to acceptable levels.

Oversized waveguide, just like standard sized waveguide, can be made with any cross sectional shape. Generally, only oversized rectangular or oversized circular waveguide is used. Only precision waveguide should be used. Precision circular and rectangular waveguides are available from precision waveguide manufacturers such as AZDAR (a division of EVERED, a British Company).

4.3.1 Oversized Rectangular

Of all oversized waveguide types, oversized rectangular waveguide is the least troublesome to use. Its ease of use derives from both its higher attenuation per foot and from the simple design of its mode filters. Losses in transitioning to and from standard rectangular waveguide are low, nearly as low as for standard sized circular TE_{01} Low Loss mode. By expanding standard rectangular waveguide correctly into oversized waveguide sizes, standard sizes (1:2 dimensional ratio) of waveguides may be used for the oversized waveguide also (WR 62 or 75).

For waveguides in general, the lower the waveguide's attenuation, the higher its sensitivity to irregularities. In comparison with oversized circular waveguide, oversized rectangular waveguide is more tolerant of irregularities, bends, or guide distortions. Mode filters are not required as often on an oversized rectangular waveguide run as on an oversized circular waveguide run.

Although not as sensitive to guide imperfections as oversized circular guide, oversized rectangular waveguide must use precision waveguide with tight dimensional tolerances. In Naval Electronics Laboratory Center Tech Note #2088, dtd 27 July 1972, two WR 112 waveguide sections were compared while being operated as oversized rectangular waveguide in the TE_{01} rectangular mode. One was precision WR 112 with dimensions +/-.001 while the other was standard WR 112 with a dimensional tolerance of +/-.003 inches. A theoretical value for the attenuation of WR 112 operating in the TE_{01} mode at 38 GHz was calculated. The precision and standard guide losses were 21% and 54% larger, respectively, than the calculated theoretical value of .028 dB/ft. Although the calculated value assumed a d.c. value for the conductivity of copper and although only a single sample of each waveguide was tested, it appears that precision waveguide must be used for oversized rectangular waveguide runs.

Besides its low attenuation per foot, another characteristic which makes the use of oversized rectangular waveguide appealing is the low transition loss. Oversized rectangular waveguide losses are usually not as low as the low attenuation per foot achievable in standard sized circular TE_{01} mode waveguide, but the transition losses are much less. Oversized rectangular transitions lose only 0.1 dB transitioning to or from standard rectangular waveguide while circular TE_{01} mode transitions lose 0.2 to 0.35 dB.

A tradeoff decision must be made when choosing how large to make an oversized rectangular waveguide. Larger waveguides cannot be manufactured to the same tight tolerances as smaller waveguides can. By using a larger waveguide to decrease the attenuation, eventually attenuation is increased more by the lower waveguide tolerances and increased sensitivity to imperfections than it is reduced by the increase in waveguide size. This optimizing tradeoff should be performed each time an oversized rectangular waveguide transmission line is being planned.

The best way to expand from standard sized rectangular to oversized rectangular waveguide is not to simply expand both waveguide dimensions

(See Figure 6) to the desired size. In standard sized waveguide, the frequency range of the waveguide is set by the longer dimension, a, of the guide (See Figure 1). The theoretical attenuation (using a d.c. value for the conductivity of copper) is given by:

$$\frac{(.0317)\left[\frac{1}{b} + \frac{1}{2}a\left(\frac{\lambda}{a}\right)^2\right]}{\sqrt{\lambda}\,\sqrt{1-(\lambda/2a)^2}} \quad \text{dB/ft,}$$

where a, b & λ are in cm.

Since increasing either the a or the b dimension will reduce attenuation and since changing the a dimension alters the frequency range of the waveguide, the best way to oversize a rectangular waveguide is to increase the b dimension only. If the b dimension is lengthened to four times its original length, then the ratio between the a & b dimensions is once again 1:2. This way, standard sized waveguides may still be used for the oversized rectangular waveguides. WR22 waveguide can be transitioned up to WR62 or WR75 in this way. Also, the rectangular TE_{10} mode in the standard sized guide is now the rectangular TE_{01} mode in the oversized guide. This happened because the long and the short dimensions of the waveguide have been switched in orientation relative to the orientation of the electromagnetic fields within the waveguide. What has been done, effectively, is to transition the waveguide around the mode rather than to transition the mode within the waveguide. The attenuation of the new TE_{01} mode in the oversized rectangular waveguide may be calculated by interchanging the a and b terms in the attenuation equation given for the TE_{10} mode above.

The simplicity of design of effective mode filters is one of the chief advantages of working with oversized rectangular waveguide rather than other oversized guides as can be seen from Figure 2, the electric lines of force of the TE_{10} mode terminate on the broad wall of the waveguide. Since these electric lines are symmetrically distributed about a line centered midway down the length of the broad wall, there is no voltage differential and, therefore, are no surface currents which exist across that line. By making a slot along this line down the center of the broad wall of a TE_{10} waveguide, the waveguide section acts as a TE_{10} mode filter, attenuating most other modes but not the TE_{10} mode. Similarly, making a slot down the center of the narrow wall of an oversized rectangular waveguide acts as a mode TE_{01} filter. This is a very simple design for a mode filter and can be manufactured easily by any in-house machine shop.

4.3.2 Oversized Circular

Use of the low loss mode in oversized circular waveguide is the lowest loss method of transferring millimeter wave power. It has been studied extensively by Bell Telephone of the U.S., CNET in France, and many others during the 1950's and 60's. Although they extensively studied the low loss mode TE_{01}, transmission of mode TE_{11} or any other circular mode is also possible through oversize circular waveguide. The real need to use any of these transmission methods arises only when transferring EHF power for distances of 100 ft. or more. Because of extremely low attenuations, these methods are even more sensitive to irregularities or bends than the oversized rectangular guide is. Mode filters are required at regular intervals in an oversized circular line to dampen out unwanted modes. Losses of 3 dB per mile are possible at millimeter wavelengths using 2 inch TE_{01} mode waveguide. For mile length runs, oversized TE_{01} mode waveguide is the only choice, but the restrictions on its use make other alternatives a much better choice for shorter runs (under 50 ft.).

4.4 DIELECTRIC WAVEGUIDE

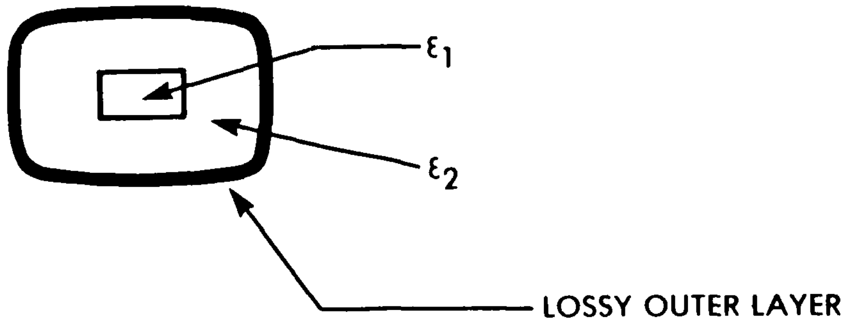


Figure 7: Rectangular Dielectric Waveguide

Dielectric waveguide is unlike other waveguides. It is not a hollow metal structure. In fact, it doesn't have conductive metal layers at all. Behaving much more like fiber optics than conventional waveguide, it bridges the gap between these two technologies. Dielectric waveguide, as shown in Figure 7, consists of a central core of relatively high dielectric constant (E_1) material surrounded by a layer of lower dielectric constant (E_2) material. The majority of electromagnetic energy propagating through the waveguide is maintained within the inner, high dielectric region. This propagation is often looked at in one of two ways: 1) As a TEM mode propagating through a region with two different dielectric constants, 2) as a low frequency fiber optic transmission line. (The electromagnetic energy is internally reflected within a central region having a high index of refraction surrounded by a region with a low index of refraction.) Because the index of refraction is equal to the square root of the dielectric constant, these two points of view are equivalent. Just as with fiber optics, the worst performance of dielectric waveguide is through minimum radius bends. Bends increase the attenuation of a dielectric waveguide and decrease its power handling capability. Just as with fiber optics, increasing the dielectric constant (or index of refraction) of the central core relative to the surrounding medium increases the performance through bends. More energy is retained within the core and less energy will be lost passing through bends. However, increasing the dielectric constant of the core, using present technology, increases the loss tangent of the central core, and increases attenuation. This technique of increasing the core dielectric constant is used to decrease the minimum radius of bend where it's required. The choice of ratio of the dielectric constants between the inner core and its surrounding material is one of the trade-off decisions which must be performed when optimally designing a dielectric waveguide.

The theory of dielectric waveguides is not new, but the recent development of a dielectric material with a low loss tangent has made low loss dielectric waveguides possible. The loss tangent is related to the amount of energy lost per foot propagating through a dielectric. Polytetrafluoroethylene (PTFE or the same materials as "Teflon") has a low loss tangent. By foaming it out to form expanded PTFE, its loss tangent can be decreased still further. Losses can be reduced to the point where a 1½ inch rectangular cross section dielectric waveguide of expanded PTFE can have losses at 44 GHz of 0.12 dB per foot. This is half the loss of rectangular waveguide (WR 22). In addition, these losses are not greatly affected by frequency. At 100 GHz, the dielectric waveguide losses can be as low as 0.3 dB per foot.

The main advantage of expanded PTFE dielectric waveguide is that it is continuously flexible over its entire length. PTFE has been used as insulation in coaxial cables for SHF and EHF transmission for years. It is resistant to vibration and flexible. Flexibility is a relative term, however, and the flexibility of a 1½ inch diameter dielectric waveguide would be comparable to the flexibility of a 1½ inch coaxial cable, which is fairly stiff, especially when jacketed. Among the disadvantages of dielectric waveguide is the relative lack of test data to verify waveguide performance. Expanded PTFE dielectric waveguide is a new development and relatively few samples of completed waveguide sections are available for testing purposes. Kollmorgen Corp. has one or two samples for evaluation. NUSC's Electromagnetic Systems Dept. has four samples for testing. The only other test data available is supplied by W.L. Gore & Associates, the sole manufacturers of this proprietary product. Test results from the manufacturer are available for each sample, test results from Kollmorgen are available, and test results from NUSC will be available soon. The most extensive test data base currently available is from the manufacturer, W.L. Gore & Associates.

Gore has produced both circular TE_{01} mode and rectangular HE_{11} mode dielectric waveguides. Of these two, the rectangular dielectric waveguide appears to be the better performer. Judging from a limited number of samples, the losses in transitioning into or out of the dielectric waveguide appear to be inordinately large. The design used for the transitions is a simple conical type which has the relatively high loss of 0.7 dB per pair. This indicates a need for development work in the area of dielectric waveguide to standard rectangular waveguide transitions.

The optimum diameter of a dielectric waveguide varies with the waveguide's operating frequency range. 40 GHz waveguides have diameters between 2.0 in and 0.75 in. 95 GHz dielectric waveguides have diameters of between 1 in. and 0.25 in. Since the minimum bend radius is 6 times the waveguide diameter, higher frequency dielectric waveguides are much more flexible than lower frequency dielectric waveguides.

For higher frequencies, dielectric waveguide appears to be an even more attractive option. Not only does the waveguide become more flexible, but its attenuation as compared to standard rectangular waveguide becomes even better. At 44.5 GHz, the attenuation of 1.5 inch rectangular dielectric waveguide appears to be somewhere between 0.1 and 0.15 dB per foot. This is an improvement over WR 22 by about a factor of 2. At 96 GHz, the attenuation of dielectric waveguide appears to be around 0.3 dB per foot. The attenuation of comparable rectangular waveguide is between 1 and 1.5 dB per foot yielding a factor of improvement of between 3 and 5 over standard rectangular waveguide attenuation. These advantages of increased flexibility and lower relative attenuation can cause dielectric waveguide to be the right choice for use at a higher frequency in the same application where it may not be the best choice for use at lower frequencies.

The measured performance of dielectric waveguide around 44 GHz is good. Two 1.5 in. diameter rectangular dielectric waveguide sections with lengths of 3 and 9 feet have total attenuations of 1 and 1.5 dB respectively from 43.5 to 45.5 GHz (See Appendix 3). These measurements imply a 0.75 dB attenuation per pair of transitions and under 0.1 dB attenuation per foot of straight dielectric waveguide. A minimum radius bend with a 9 inch radius increases attenuation less than 0.25 dB per 90°

of bend. A bend with a larger than minimum radius increases attenuation 0.25 dB per 360° bend. The maximum power handling capacity of the waveguide exceeds 100 W through a minimum radius bend. Bending the waveguide more sharply than the minimum radius bend causes excessive power loss and a resultant heating up of the outside lossy layer of the guide. The waveguides are generally designed to pass a 10% bandwidth. Some dielectric waveguide test data is included in Appendix 3.

Dielectric waveguide is not perfect however, and still requires some development, especially in the area of shielding. Coverings are required on the waveguide both to prevent electromagnetic interference (EMI) and to protect the dielectric material from physical damage. In an operational environment, where other electronic equipment is present around the dielectric waveguide, shielding becomes necessary to prevent the waveguide's signals from interfering with the surrounding equipments' signals and vice versa. In addition, the presence of a conductor near an unshielded dielectric waveguide alters the electromagnetic fields within the guide and can increase attenuation. Early samples of dielectric waveguide were unshielded, which caused problems whenever the waveguide was tested in the proximity of a conductor. Now, all dielectric waveguides are shielded, and EMI shielding is no longer a problem.

Physical damage is a danger to expanded PTFE dielectric waveguide just as it is to metallic waveguides. The expanded PTFE material is not very resilient. Crimping or dinging a dielectric waveguide may permanently degrade its performance. Due to the relative softness of dielectric waveguide in comparison with a metal waveguide, dielectric guide must be protected if the possibility of extremely rough handling exists. Because of the newness of the dielectric waveguide, an effective sheathing technique has not yet been tried in an operational scenario but there are several alternatives. Gore intends on using either the stainless steel armor or the hardened steel spring sheathing which has proven extremely successful with their line of microwave cables. Either of these techniques will probably work well. For normal usage, an aluminized Kapton EMI shield with a plastic sheathing is all that's required.

In summary, dielectric waveguide is a unique type of waveguide with unique properties. In any application over 7 feet in length, dielectric waveguide sections will have lower losses than standard WR22 rectangular waveguide. If a waveguide, which is flexible over its entire length is required, dielectric waveguide is the answer, provided a 1.5 inch diameter and 10 inch bend radius can be tolerated. Some effort is underway in dielectric waveguide developing dielectric waveguide transitions with lower attenuation and in shielding the waveguide from physical damage. At higher frequencies in the EHF range, its somewhat bulky diameter and intolerance for tight bends diminish so that dielectric waveguide is an even more attractive option at these frequencies. Even at 44 GHz, it is an option which should be considered.

SECTION 5

THE DECISION PROCESS

5.1 DESIGN CONSTRAINTS

In each application where waveguide losses are to be minimized, there are requirements placed upon the waveguide caused by physical restrictions on the waveguide's path. Each of the technologies just presented has its capabilities and limitations in meeting these physical restrictions while still maintaining low losses. By first determining the physical requirements caused by the installation and then choosing the lowest attenuation method which fits those constraints, the lowest attenuation technology can be chosen.

5.1.1 Installation Derived

The installation in which the low attenuation waveguide will be used determines both the overall length of the waveguide run and the bendability which will be required of the waveguide. The overall run length can be measured for each installation. This is a straight-forward end-to-end measurement of the waveguide run from start to finish. The bendability constraint needs to be explained more fully.

Bendability can be categorized as either non-bendable, rigidly bendable, semirigidly bendable, or flexible. Each installation sets the minimum bendability requirements for the waveguide being used in that installation. Not all installations can use a straight run of waveguide. Take, for example, an aircraft where the transmitter is located in the electronics bay in the belly of an aircraft and one or more antennae are located on top of the fuselage. It may not be permissible for a waveguide to cross straight through a crew compartment in-between. In this case at least rigid bends would be required. Semirigid bends often become necessary as a result of the real world of manufacturing tolerances. Not all aircraft are exactly identical in size. If a transmitter/antenna system is to be mass produced and installed on all aircraft of a particular type, when it comes time to install the waveguide sections on the aircraft not all of them will fit exactly. To compensate for these minute differences between installations, semirigid sections or "snake lines" can be used rather than individually customizing each installation. These sections are invaluable as timesavers during maintenance or installation. Semirigid sctions have their limits as to the number of times which they may be bent before metal fatiguing or failure occurs. If the installation calls for repeated flexing, flexible sections are required. Examples of this need would be sections located at a wing root going into a wing or sections periodically spaced down a long run in a fuselage to localize bending stresses caused by aircraft flexing. Such localizing relieves bending stresses from the majority of the waveguide run length.

Table 7 - Technologies and Bendabilities Arranged by Attenuations at 44 GHz

Technology	Attenuation(dB/ft)	Bendability
Oversized circular TE_{01}		
2" Diameter	.00055	Non-Bendable
1" Diameter	.004	Non-Bendable
TE_{11}		
2" Diameter	.0055	Non-Bendable
Standard Sized Circular		
TE_{01}	.036	Rigid(18"Radius)
Oversized Rectangular		
TE_{11}	.097	Rigid
WR62	.042	Non-Bendable
Rectangular 1.5"	.12	Flexible (Dielectric)
Square .224"	.15	Rigid
Rectangular WR22	.229	Rigid
Rectangular Flexible	.6	Flexible/Semirigid
Circular TE_{01} Internally Corrugated Bends	.4	Flexible/Semirigid

5.1.2 Technology Inherent

Each waveguide technology has its own limits of bendability. The bendability of waveguide technologies which can achieve attenuations less than standard rectangular waveguide at 45 GHz are listed in order of increasing attenuation in Table 7. This arranges information on the bendability of waveguide technologies into an order of preference for those technologies.

5.2 THE BOTTOM LINE: THE CHOICE FOR LOWEST ATTENUATION

5.2.1 Bendability, Run Length, and Attenuation

By looking at the bendability requirements of an installation, the preferential order of Table 7 can be used to choose the low attenuation technologies which can satisfy those bendability requirements. If no bends are required, then any technology can be used. However, the lowest attenuation choices would be oversized circular TE_{01} mode, oversized circular TE_{11} mode, Standard sized circular TE_{01} mode, or oversized rectangular waveguides, in that order. If bends are required (rigid bends), then all oversized waveguides are eliminated leaving circular TE_{01} mode, circular TE_{11} mode, dielectric waveguide, or square waveguide in that order of preference. If semirigid bends are required, then only standard sized circular TE_{01} mode or dielectric waveguide can outperform flexible WR22 waveguide in terms of attenuation. The same two choices are again the only two possibilities where flexible bends are required. Therefore, by knowing the bendability requirements of a particular installation, and by using Table 7, unsuitable technologies can be eliminated from consideration. For applications where no bends are required, the range of low attenuation choices can be narrowed further based upon the length of the waveguide run.

First of all, the oversized circular modes are extremely sensitive to imperfection and their ultra-low attenuations are normally not required unless the length of a waveguide run exceeds 40-50 feet (at 44 GHz). Standard sized circular TE_{01} mode or oversized rectangular waveguide are both much easier to work with and can have attenuations as low as 1.8 or 2.1 dB per 50 ft of waveguide, respectively. The ease of working with these two waveguides comes from the simplicity of design of the filters used for the circular TE_{01} mode or rectangular TE_{01} mode waveguides. In addition, their somewhat higher attenuations make them much less sensitive to waveguide irregularities than either of the oversized circular waveguide modes.

If bends are required, then the standard sized circular TE_{01} Low Loss mode emerges as the preferred choice. Not only is its attenuation lower than either circular TE_{11} mode or square waveguide, but it has a circularly polarized propagation mode and does not have the problems associated with the linear polarization of either circular TE_{11} or square waveguides. In addition, the filters for the TE_{01} mode are much simpler than those for the TE_{11} mode in circular waveguide.

If either semirigid or flexible sections of waveguide are required, then only two alternatives can provide a lower attenuation than flexible sections of rectangular waveguide. These two waveguides are dielectric

WAVEGUIDES

TYPE	dB PER FT	dB PER PR OF TRANSITIONS	BENDABLE	LOSS 5 FT	LOSS 20 FT
DIELECTRIC	.12	.7	FLEXIBLE	1.3	3.1
RECTANGULAR WR22	.229	0	RIGID ONLY	1.2	4.6
	.6	0	FLEXIBLE	3.0	12.0
SQUARE	.15	.1	RIGID ONLY	.85	3.1
CIRCULAR TE_{11}	.097	.2	RIGID ONLY	.7	2.1
TE_{01}	.036	.6	FLEXIBLE	.8	1.3
OVERSIZED					
RECTANGULAR WR62	.042	.2	NO	.41	1.0
WR75	.031	.2	NO	.35	.8
OVERSIZED					
CIRCULAR TE_{11} 2"	.0055	.3	NO	.3	.4
TE_{01} 1"	.[illegible]4	.7	NO	.7	.8
TE_{01} 2"	.00055	.7	NO	.7	.7

TABLE 8: STRAIGHT WAVEGUIDE ATTENUATIONS (44 GHz)

waveguide and circular TE_{01} mode waveguide using internally corrugated bends. In general, if an installation requires that a waveguide be flexible over its entire length and if a 2 inch diameter can be tolerated at 44 GHz, then dielectric waveguide will provide the lowest attenuation. If the waveguide run can be made using rigid bends or straight sections for the most of the run with flexible or semirigid sections only required in several spots, then circular TE_{01} mode will provide the lowest attenuation. Two additional deciding factors are: if a bulky waveguide (2 inch diameter at 44 GHz) cannot be tolerated or if tight radius bends (under 9 inch at 44 GHz) are a must, then dielectric waveguide cannot be used and circular TE_{01} mode is the choice. The restriction of 9 inch minimum radius bends for 44 GHz dielectric waveguide relaxes considerably to a 4 inch minimum bend radius at 100 GHz if a higher frequency system is being considered. Dielectric waveguide will become an even more attractive option as lower loss transitions are developed. The higher price of dielectric waveguide may be offset by the fact that it requires no dry air pressurization system, and it may significantly simplify the installation or maintenance of an operational system.

5.2.2 Expected Attenuations

If we include the losses of a pair of waveguide transitions (to WR22 and from WR22), we can estimate the total attenuation of a straight waveguide run using any technology. Table 8 shows the expected losses for a 5 foot and for a 20 foot length of waveguide with a transition at each end of the run. Remember that the dB per foot for waveguides is highly

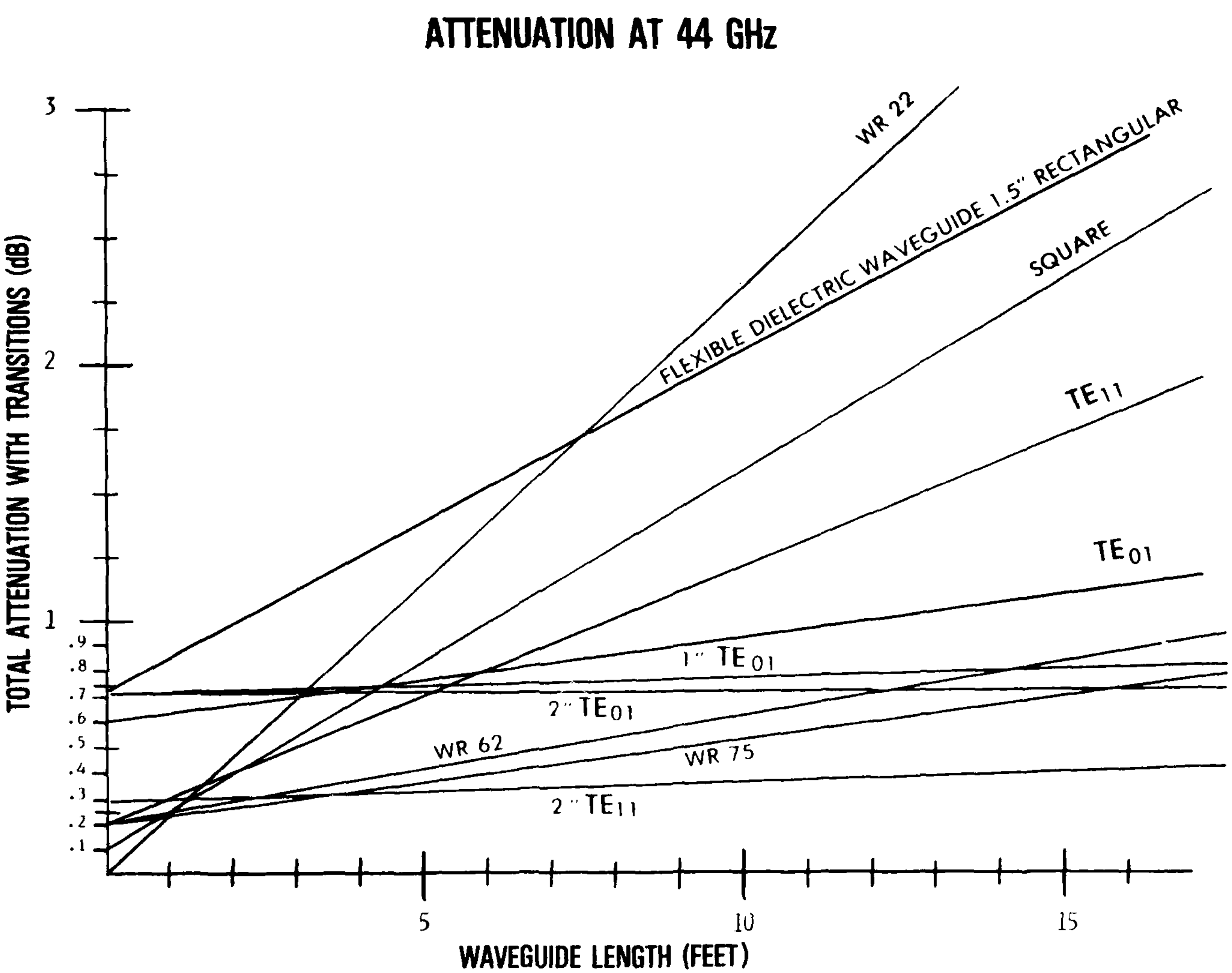


Figure 8: Waveguide Attenuation vs. Length

BENDABLE		
WR22		17W LEFT
DIELECTRIC WAVEGUIDE		25W LEFT
CIRCULAR	TE_{11}	31W LEFT
	TE_{01}	37W LEFT
STRAIGHT		
OVERSIZED		
RETANGULAR		
	WR62	40W LEFT
	WR75	42W LEFT
CIRCULAR		
	TE_{11}	46W LEFT
	TE_{01}	43W LEFT

TABLE 9: Power Remaining After a 20 ft. Run From a 50W Transmitter.

dependent upon the tolerances used in manufacturing and on surface resistivity within the guide. Remember also, that the dB per pair of transitions can also vary. TE_{01} mode transitions vary from .2 to .7 dB per pair depending on transition type, manufacturing tolerances, and any reactive components or bends used later in the waveguide run.

If the results shown in Table 8 are graphically depicted using the length of a waveguide run as the horizontal axis, then we generate Figure 8. If we look on Figure 8 at distances of 6 feet and longer, the five technologies with the highest attenuation are also the only five bendable technologies; the lower five technologies are all oversized waveguides and unbendable. The significance of Figure 8 lies mostly beyond 4 feet in length because the attenuation of 4 feet of WR22 at 44 GHz is less than 1 dB. Since most systems can tolerate a 1 dB signal to noise degradation, there is usually no real advantage to using a more expensive technology than rectangular waveguide.

5.2.3 Conclusion and Recommendations

If a rectangular waveguide run exceeds 4 feet in length, it should be looked at closely. Replacement of a 20 foot run with standard sized low loss mode waveguide can save 3.3 dB of attenuation, an example of losses is shown in Table 9. The cost of the waveguide may be more but overall savings may be realized in terms of lower transmitter power and cost, increased transmitter reliability, decreased cooling requirements, and decreased prime power requirements. For airborne systems, these are all very real considerations.

In short, the basic way to minimizing waveguide losses is to keep the run length to a minimum and to minimize the number of bends required. If a straight run of waveguide is possible, then examine oversized rectangular waveguide or low loss mode TE_{01} mode circular waveguide. If rigid bends are required, then use circular TE_{11} mode for short runs and low loss mode for long runs. Corrugated electroformed bends should be used with low loss mode where tight radius bends are required. Where semirigid or flexible bends are required, again use TE_{01} mode circular waveguide with electroformed, corrugated bends, but use materials for the bends which will not work harden if flexibility is required. If flexibility or semirigidity is required over the entire length of a waveguide's run, then dielectric waveguide should be considered. If tight bends (less than 9 inch radius) are required at low EHF frequencies (44 GHz) then dielectric waveguide cannot be considered.

Many savings can be realized by reducing waveguide losses. Power consumption, cooling requirements, overall system weight, operating temperatures, reliabilities, weather resistance, and volume requirements may all be improved. Although these technologies are more expensive per foot, the overall system may realize a cost reduction. Components should be purchased and tested beforehand to verify the estimated performance and to estimate production lead times. By properly considering all of the alternatives, the optimum waveguide system may be selected and better performance or a cost savings realized.

APPENDIX 1

Abridged Version of MIL-W-23068

MILITARY SPECIFICATION

Waveguide

RIGID, CIRCULAR

1. Scope

1.1 Scope. This specification covers circular, rigid waveguides as fabricated in bulk at the mill. Waveguides may be seamless or laminated stock supplied in aluminum alloy, brass, copper, magnesium-base alloy, or silver alloy. The term "circular" applies to both the inside and outside geometry.

1.2 Classification

Type designation.
1.2.1 The type designation shall be in the following form, and as specified.

Component
1.2.1.1 Circular, rigid waveguides are identified by the three-letter symbol WRC.

Frequency
1.2.1.2 The frequency is identified by a three-digit number and a letter. The number identifies the minimum operating frequency in the TE_{11} mode in megacycles, and the letter identifies a multiplier in accordance with table I.

Table I. Letter multiplier

SYMBOL	MULTIPLY BY
U	1
D	10
C	100
K	1,000

Bandwidth ratio.
1.2.1.3 The nominal bandwidth ratio is identified by the two-digit number "14". The number is the nominal bandwidth ratio multiplied by 10.

Material
1.2.1.4 The material is identified by a one-letter symbol in accordance with table II.

Table II. Material

SYMBOL	MATERIAL
A	Aluminum alloy
B	Brass
C	Copper
M	Magnesium-base alloy
S	Silver alloy

WRC — Component (1.2.1.1)

312U — Frequency (1.2.1.2)

14 — Bandwidth radio (1.2.1.3)

A — Material (1.2.1.4)

APPENDIX 2

Bibliography of TE_{01} Mode

BIBLIOGRAPHY of TE_{01} MODE

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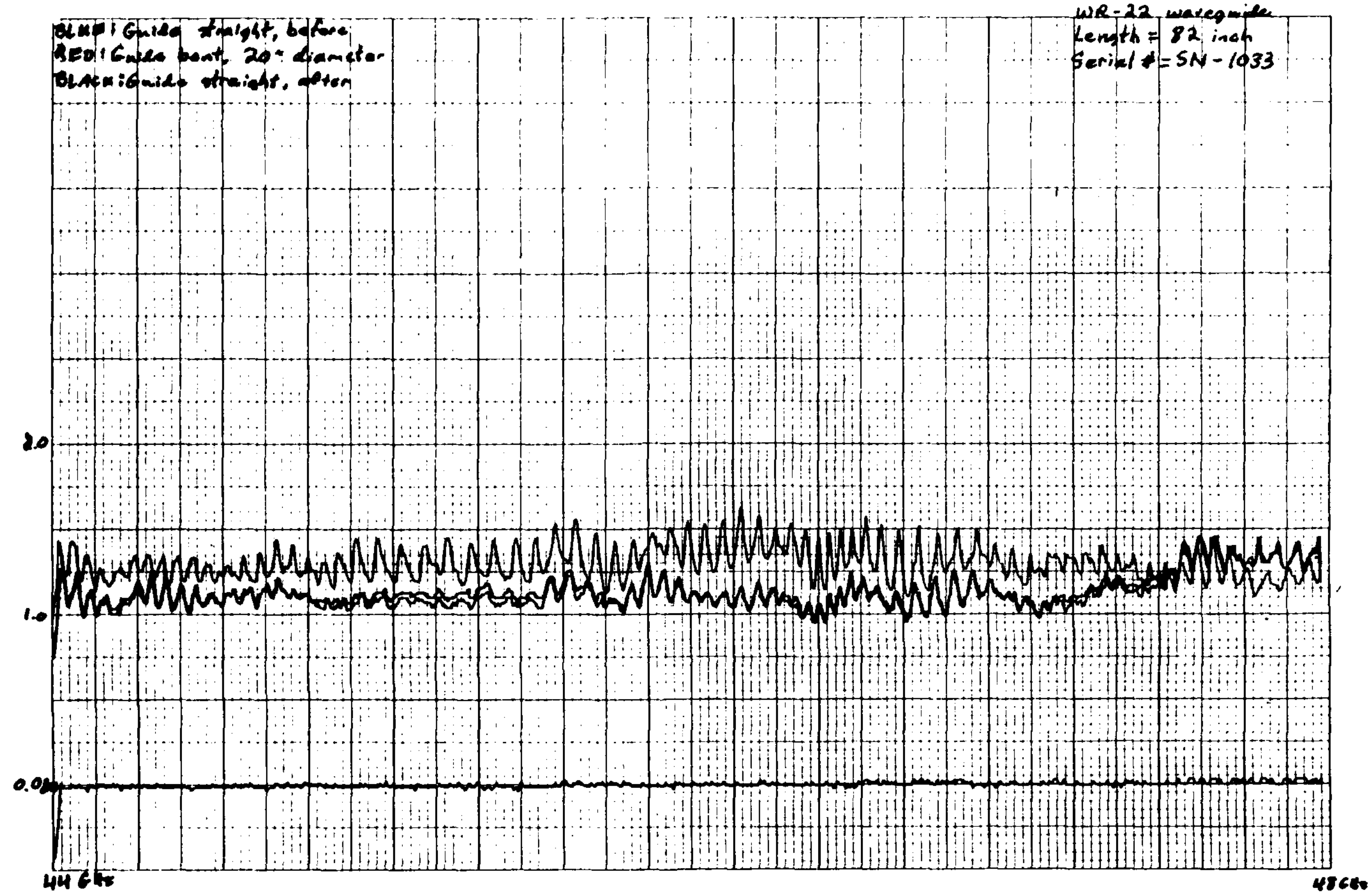
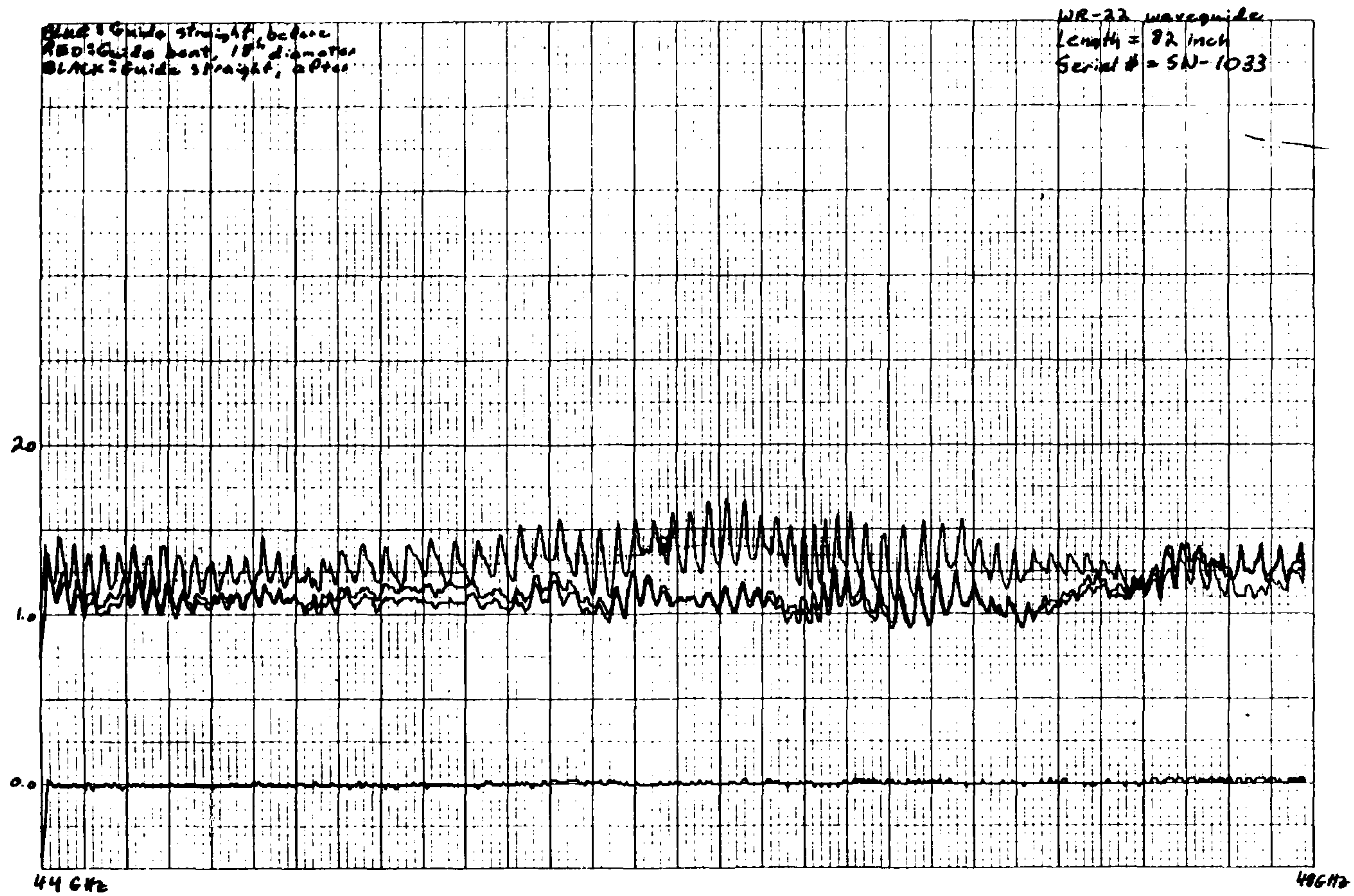
APPENDIX 3

Dielectric Waveguide Test Data

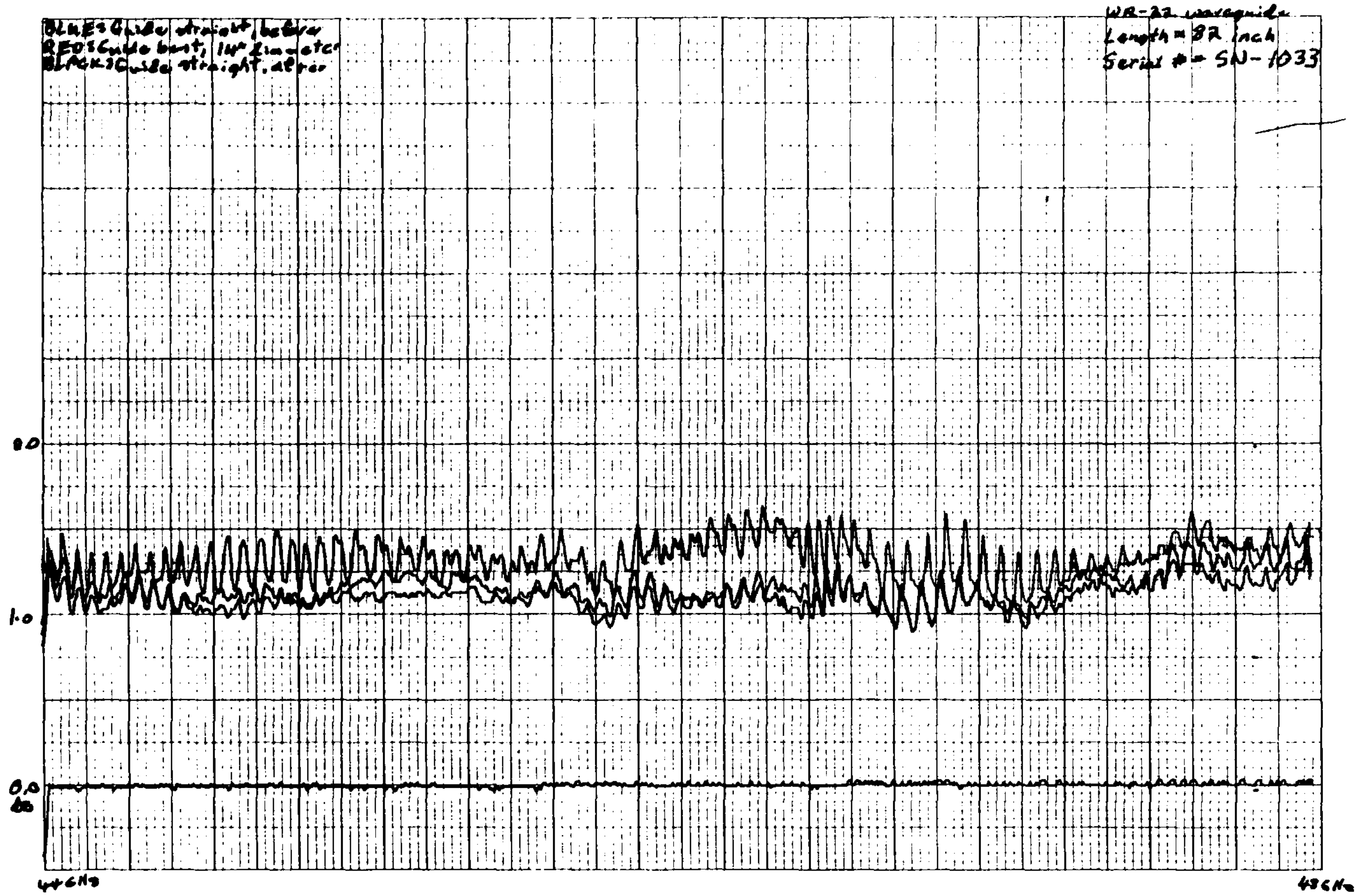
(Test data supplied by the manufacturer, W.L. Gore & Associates, Inc.)



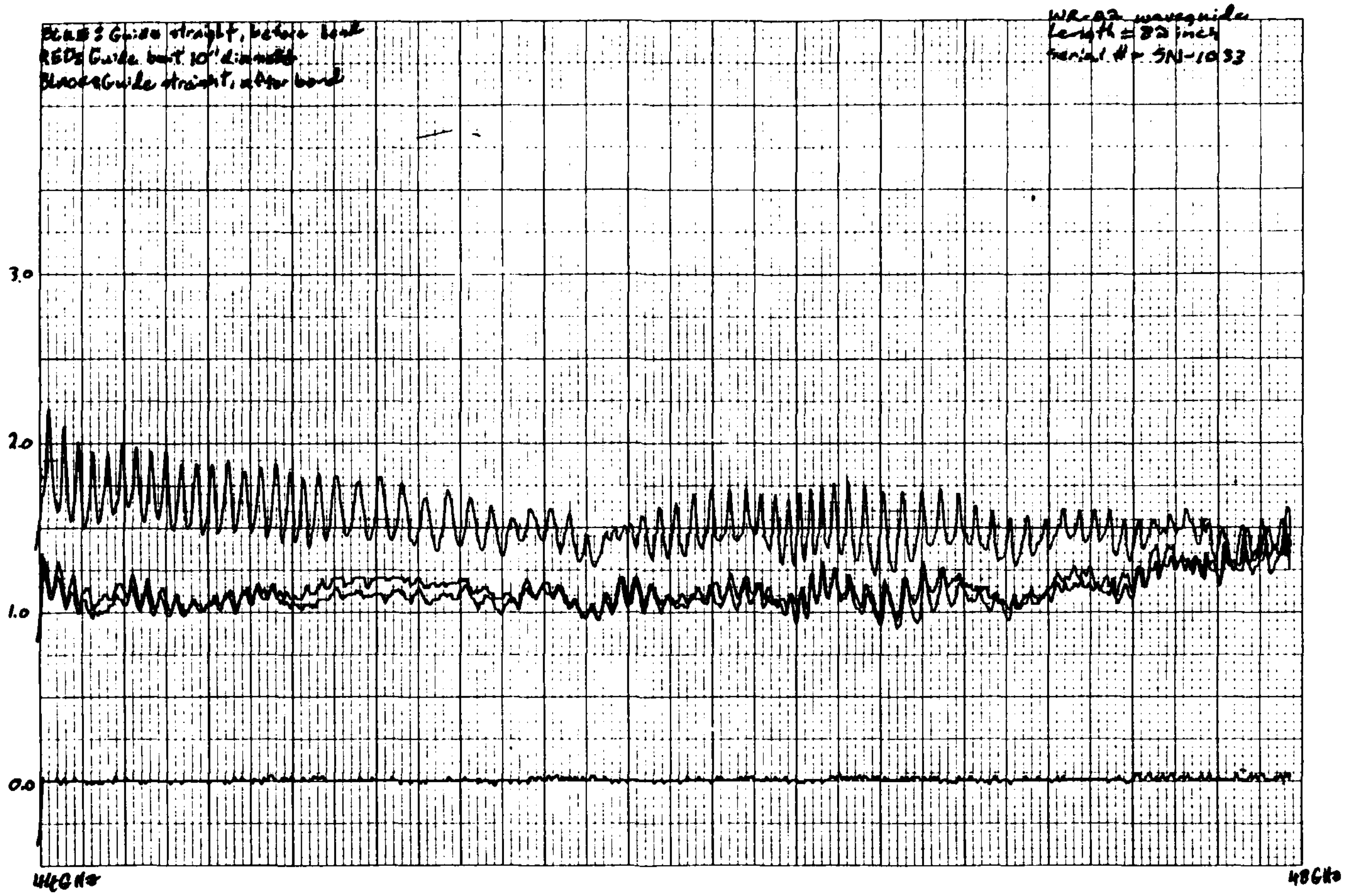
82 in WR22 Dielectric Waveguide Bent With 10 in radius (top) and straight (bottom)



82 in WR22 Dielectric Waveguide Bent with 9 in radius (top) and straight (bottom)



82 in WR22 Dielectric Waveguide Bent with 7 in radius (top) and straight (bottom)



82 in WR22 Dielectric Waveguide Bent with 5 in radius (top) and straight (bottom)

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