NATIONAL RADIO ASTRONOMY OBSERVATORY
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VLA PROJECT

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MILLIMETER WAVEGUIDE SYSTEMS IN THE WORLD

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In several countries, research and development has been done on millimeter waveguide transmission systems for more than thirty years. In the United States, United Kingdom and Japan, a long experimental waveguide line was constructed and field tests were done with promising results. Millimeter waveguide systems are technically almost ready for commercial application in the public communication system. But the increase of demand for a large capacity transmission system has not arisen as quickly as expected and many doubt that the waveguide system can remain as the best transmission system carrying a large capacity. In the meantime, a promising alternative system, the optical transmission system, is being investigated.

This report is intended to review the present situation of millimeter waveguide transmission systems all over the world.

The information contained within was derived from the following three conferences held in 1976, the discussions during the trip to these conferences and research facilities and the recent publications.

1. International Conference on Communications (I.C.C.)
   (June 14-16, 1976. Philadelphia, Pennsylvania)
2. International Microwave Symposium (I.M.S.)
   (June 14-16, 1976. Cherry Hill, New Jersey)
3. IEE Conference on Millimetric Waveguide Systems
   (Nov 9-12, 1976. London, England)

So special design and development are required for antenna waveguide.

Reduced diameter dielectric lined waveguide has been studied mainly in the United Kingdom. The diameter is 18mm and it has been studied in 30-110 GHz. Development and improvement work are in progress. It should not be very hard to develop 20mm diameter waveguide in 27-53 GHz. But the very limited flexibility might cause problems during installation. Keeping the eye on improvement could be recommended.

Coupler

The VLA is the only group to study a waveguide system with many couplers in line which means we have to build our own criteria for coupler specifications. Some useful information could be gotten from the experiences in designing signal distributors especially for beam splitter couplers. Sector couplers seem to be unique but have never been explored.

Others

Gas windows have been developed in several countries, but return loss is 20-35dB in those windows. For maintenance and realiability, it is better to have many gas windows, but in such cases high return loss is required. It seems impossible to introduce any of these into the VLA waveguide system except for very few. The difference in transmission technique, such as modulation, detection, etc., should be realized and a new type of gas window should be developed.

IV. Application of Techniques to VLA Waveguide System

Main Waveguide

In the VLA waveguide system, 27-53 GHz is used and the loss is required less than 1.6dB/km. As seen in Table 1, some waveguide can fill this requirement but most of the waveguide would require protection duct. When installation technique is limited to direct burial, 60mm helix waveguide with steel jacket would be the only waveguide that could meet the requirement, leaving some unknown factors to combination use of helix waveguide and dielectric waveguide. The diameter of 60mm seems to be close to optimum. 50mm is too small and 70mm would cause too large a loss increase in direct burial.

The direct burial installation gives us some worry about the future loss deterioration. Only few systematic studies on direct burial installation were done besides the Japanese tests. But the tests that were done in Japan seem to be too critical compared with the actual situation at the VLA site. Judging from Japanese tests, data from B.T.L.'s directly buried waveguide, and recent data from the VLA waveguide, if the waveguide would be correctly installed, the loss after installation could be minimized and would not go up as rapidly. Careful checking of installation conditions such as soil, temperature, machine and so on could be recommended.

Antenna Waveguide

Generally these components can be considered for sharp bends.

1. Corner Waveguide
2. Reduced diameter semiflexible helix waveguide
3. Reduced diameter dielectric lined waveguide

Regarding corner waveguides, it is better to have a large diameter, but it makes the installation difficult. No corner waveguide of less than 50mm diameter has ever been reported.

Reduced diameter semiflexible helix waveguide was developed only in Japan and is used in the route that has many sharp bends. They were designed in 43-87 GHz frequency range and 14mm in diameter.

the direction by a specified angle in one plane, double corner waveguide consisting of two corner waveguide rotating about each other at a suitable span is used to achieve a complexed angle change.

In the British system, 18mm diameter dielectric lined waveguide is considered to be used for a similar purpose. In theory, the possibility of low-loss was shown a long time ago. Bending the waveguide into a complex configuration and maintaining that configuration during installation are problems to be dealt with. In recent time, remarkable progress has been made and it is close to completion.

In the B.T.L. waveguide system, no sharp bends are planned to be used between repeater stations. Just when waveguide has to turn up to a repeater in the manhole, corner waveguide is used.

U.S. 45-50km

U.K. 20-30km

Japan 15km (except inside cities)

Maintenance

It is common to all the countries that waveguide is filled with nitrogen gas to remove the oxygen absorption. But some difference can be found in the techniques to supply and maintain it. In the English waveguide system, nitrogen supplied from gas bottles keeps flowing to remove the water vapor and oxygen coming from epoxi resin or penetrating from outside. In the B.T.L. and Japanese systems, waveguide is pressurized at a certain level and its drop is monitored. The space between the waveguide and protection duct is also filled with dry gas to prevent water penetration and to locate the damage points at emergency time. The gas used for this purpose is as follows:

N_2 gas; B.T.L.

Dry Air; Japan, the United Kingdom

In such a gas system, waveguide gas window is required. In the B.T.L. and Japanese waveguide system, it is installed only at the repeater station, but in the British system, it is installed at the interval of about 2km. In the French system, the waveguide gas window is considered to be important and it was installed almost every 2km in the experimental line, because waveguide is installed directly underground and it does not have another gas system as other countries have. The diameter of the gas window is the same as trunk waveguide except in Japan.

Special Waveguide for Sharp Bends

Many corner waveguides and flexible waveguides are used in Japan. But as is well known, corner waveguide generates TE_{on} ($n \geq 2$) mode and causes signal distortion. TE_{on} mode filter has been developed to solve this problem. As single miter corner waveguide can only change

United Kingdom and plastic roller is used in Japan to reduce the friction between waveguide and protection duct and to hold the waveguide in the duct.

Some difference can be found on the treatment of heat stress raised by temperature change. In the British system, waveguide is pulled to compensate heat stress in the cold season. In the Japanese system, expansion waveguide is used to absorb elongation or shrinkage. In B.T.L. system, waveguide is fixed in the manhole and expansion and shrinkage are absorbed by the waveguide supporting system.

Waveguide Route

The waveguide installation route in Japan will be selected on the same base as that of coaxial cable and will have many moderate and sharp bends. Their experimental line route was selected so that it could represent the future typical route and problems associated with bends have been explored. Even in the suburbs, waveguide is expected to be installed in one part of public road with steel duct protection. Another remarkable feature in Japanese route selection is that waveguide is planned to be installed into big cities such as Tokyo through an underground cable tunnel that has many sharp bends. An experimental line that had more than 50 sharp bends in 3.8km was constructed and its performance was evaluated.

The waveguide routes that has been considered in the U.S. and the United Kingdom are much simpler. Most of the waveguide is expected to be installed across the country along special favorable routes for waveguide. Minimum radius is planned to be 150m and 100m in the U.S. and the U.K. respectively while it is 30m in Japan. But in the U.K. if the performance of reduced diameter dielectric lined waveguide could be improved in the future, sharp bends of less than 1.8m radius would be used more and it would give more flexibility to route selection.

The repeater span strongly depends upon the waveguide route. Reflecting above mentioned situations, it is expected as follows:

being used are as follows:

1. Flange Welding (U.S.)
2. Thread Coupling Sleeve (Japan)
3. F.R.P. Coupling Sleeve with Epox Injection (U.K.)
4. Flange Clamping (France)

Welding seems to be the best method both in gas-seal performance and in connection accuracy, but it requires a special welding machine with small heat effect on waveguides.

Waveguides that were used in experimental line of longer than 3km are listed in Table 1 with typical performances.

Waveguide Installation

Installation techniques that are prepared for actual use can be classified into two kinds.

1. Duct Protection (B.T.L., U.K., Japan, West Germany)
2. Direct Burial (France, NRAO)

Even in duct protection, many variations can be found. Steel tube is used in B.L.T., B.P.O. and N.T.T., but its dimension is different in each case. They have 132, 105, and 150mm inner diameter respectively. Waveguide supporting system in duct and waveguide installation route and location seem to have made such a difference. It is common to three countries that steel tube is welded at the connection part to get higher reliability and gas maintenance.

Protection duct is installed prior to waveguide installation. Waveguide is pushed into it in B.T.L. and U.K. from ground level having a leading duct section. In contrast to this, waveguide is pulled into the duct in Japan from special manholes.

The B.T.L. waveguide system has an excellent waveguide supporting system consisting of spring mounted rollers and the waveguide is held in protection tubes so that the power spectrum density of the waveguide curvature in higher mechanical frequency is suppressed. The epoxi sleeve pre-fixed to the waveguide is used in the have a configuration that gives a relatively small loss increase in curved sections and does not always give as high spurious mode absorbing performances as helix waveguides in the United States and Japan. In electrical performance, it is not essential for English and French helix waveguide to be without a steel jacket. In fact, helix waveguide in a steel jacket that gives a similar performance as the waveguide that has small loss increase in curved sections is under study in France. As far as mass-production and cost are concerned, helix waveguide without steel has many merits. But when installation is concerned, it requires other mechanical protection especially when it is installed directly underground. Experiences of installing helix waveguide underground wihtout any mechanical protection in France, tell us its importance.

Several kinds of dielectric lined waveguide have been developed in Japan, the United States, and West Germany, the biggest merit of which being their low-loss in a curved section. The construction of the tube has been very important as it requires high dimensional accuracy. It was easier to get required accuracy in steel tubes than in aluminum or copper tubes and steel is less expensive and stronger than the others. As a result, the configuration that has copper plating inside the steel tube and then dielectric material, has become common. In such a waveguide, the bonding of dielectric material, usually polyethylene, to copper plated surfaces used to be one of the most difficult. Several techniques have been developed and some efforts are still being made in this area to improve its reliability and electrical performance.

Development of dielectric waveguide has been made in West Germany, using aluminum tube. The inner surface is oxidized instead of being bonded with dielectric material. In recent days, dimensional accuracy has been improved.

C. Connection

Connection of waveguide is a very improtant factor in waveguide systems and many methods have been investigated. It usually has a relationship with waveguide configuration and cannot always be used with all types of waveguide. The techniques that are

III. Review of Waveguide Technique

Waveguide Design

Various types of waveguide have been developed in different countries. They were designed on different basis and philosophy from country to country and have different diameters, configurations, and performances. Waveguide itself has a close relationship with route selection, installation, operation frequency and economy of the waveguide system. Therefore, it is not possible to easily determine which one is the best for international standardization.

A. Diameter

Inner diameter of the waveguides in the United Kingdom, France and Italy is 50mm, and that in Japan is 51mm. Waveguides in the United States and West Germany have larger diameters, being 60mm and 70mm respectively. Ohmic loss of the waveguide comes down and loss increase caused by dimensional imperfections goes up with the increase of both diameter and frequency. Therefore, optimum diameter strongly depends upon operational frequency and waveguide dimensional imperfection, especially the straightness of the waveguide before and after installation and route bends. Generally, when operational frequency becomes lower, the optimum diameter becomes larger.

B. Configuration

Practical TE_{01} mode circular waveguide can be classified into two kinds, helix waveguide and dielectric lined waveguide. The waveguides that have been developed belong to one of the above catagories but when materials and design philosophy are concerned, many variations can be found.

The helix waveguides that have been developed in the United Kingdom and France do not have steel protection jackets while those in the United States and Japan do. They are designed on the assumption that only one kind of waveguide suitable for mass-production should be used in actual waveguide lines. They in other countries, comparative theoretical and experimental investigations have been made with waveguides and evaluation formulas and computer programs for optimization of waveguide systems have been established. Waveguides made abroad have been tested and continuous circular waveguide of their own design, in long lengths, is under the first stage of development.

waveguide are required.

At this moment, there is no urgent requirement for a large capacity transmission system but they are investigating the feasibility of a waveguide system in the future. The future application proposal will be announced soon and it may not include the application of a waveguide system.

France

In 1963, research was started on millimeter waveguide systems. 10km of proto-type waveguide was installed near Paris in 1971 and 15km of test line was constructed in Lannion in 1973, using waveguide that was produced from the continuous process.
The features of this test line are as follows.

1. Helix waveguide produced from continuous process was used.
2. It was installed directly underground.

The transmission performance was not very good and some efforts are being made on improving the waveguide design and installation without missing the above features. A new test line is expected to be installed in 20km lengths starting with 5km in 1977.

West Germany

The research has been continuing for almost twenty years in West Germany and during this period, three experimental lines of 3km length were installed using different kinds of waveguides. One of the remarkable features of their waveguide is its 70mm inner diameter. The performance in relatively lower frequency is reasonably good in improved waveguides. Since they have an excellent coaxial cable transmission network with a surplus capacity, they will not require a large capacity transmission system in the near future and as a result, are going to completely stop research work on the millimeter waveguide system within two years.

Italy

Research was started in Italy in 1967. Considering the advance

The features of their waveguide system are as follows.

1. Lightweight and cheap helix waveguide suitable for mass-production is used.

2. Only one kind of helix waveguide is used.

3. Reduced diameter waveguides are used in sharp bends.

They still have some minor problems that have to be solved, but they have a concrete plan to install 143km waveguide line between Bristol and Reading and put it into commercial use by 1982. This is the first concrete proposal that waveguide would be used in the public commercial telephone network. While the United States and Japan await the demand to arise, the urgent and special requirement in England for a new transmission medium in trunk communication lines has been realized. In addition, they are eager to export their technique to other countries, and one waveguide company (B.I.C.C.) has already supplied waveguide to several European countries such as France, West Germany, and Italy.

Japan (at Nippon Telegraph and Telephone Public Cooperation)

In Japan, they installed two lines of 4.2km long waveguide directly underground in 1965 and 1966 after developing 51mm helix waveguide and dielectric lined waveguide. After installation, studies were made on installation methods and using a new installation technique, 17.4km of waveguide was pulled into steel conduit in 1972 and 1973. Field evaluation tests have been done with good results using this line. In 1975, 3.8km waveguide line was installed in cable tunnel in one of the crowded parts of Tokyo. The route had many sharp and complicated bends and it required some special waveguides such as corner waveguide, TE_{on} mode filter, reduced diameter flexible helix waveguide and so on.

The features of the Japanese waveguide system can be listed as follows:

1. Waveguide routes are designed on the same base as coaxial cable and they contain many bends.
2. Waveguide is expected to be installed to the terminal stations located in the center of big cities through cable tunnels that have many sharp bends. Special waveguide components such as corner waveguide, TE_{on} mode filter, flexible

II. Present Situation in Each Country

The United States (at Bell Telephone Laboratories)

Research and development have been done at Bell Telephone Laboratories for more than twenty years. Initially, 50.8mm helix waveguide was developed and in 1963, part of it was installed directly underground with the rest installed in steel ducts. Remarkable loss increase was found in the directly buried waveguide by 1967. They then changed the waveguide diameter from 50.8mm to 60mm.and made many efforts in developing low-loss dielectric lined waveguide as well as developing new installation techniques. In 1974 and 1975, 14km long waveguide line was installed for Field Evaluation Test and many tests have been done. The features of their waveguide system are as follows.

1. Waveguide line consists of 99% dielectric lined waveguide and only 1% of helix waveguide.
2. Waveguides are connected by welding.
3. The loss of waveguide is less than 1dB/km across 30-110 GHz frequency band.
4. Waveguide supporting system and well studied dielectric lined waveguide are supporting the above mentioned excellent loss performance.

Techniques are almost complete and ready for actual commercial application, but the demand for a large capacity transmission system has not come up as quickly as previously expected. Expectations are for implementation of this system around 1986, but they are not sure if it will be the best transmission system at that time.

The United Kingdom (at British Post Office)

Research and development have been greatly stimulated in the United Kingdom especially in the last ten years. They developed enough technique to install 14.2km long field test line by 1975. Many tests on waveguide itself and terminal equipment are underway.

installation technique, maintenance, route selection and so on vary from country to country. These factors have a close relationship to one another, and reflect special situations in that country such as geography, population density, economic growth and so on. It is impossible to simply determine which country has the best technique.

In the following section, some details of the waveguide system in each country are reviewed and in the third section, techniques that have been developed in the various countries are reviewed and compared.

I. General Status of Research and Development

Research and development work has been done for a long time in several countries and remarkable progress has been made in these years. In Japan, France, the United States and the United Kingdom, 14 - 22km long waveguide lines were installed in 1972 to 1976 for field evaluation tests. In West Germany and Italy, some studies have been continued. In these countries, research and development work is almost completed or close to the goal. Parallel to the technical study, economical studies have been done on the waveguide system with favorable results. The cost per channel under full operation is expected to be from one-third to two-thirds of the cost of the coaxial cable transmission system. The waveguide system, however, usually requires a larger initial investment than other mediams.

The demand for a large capacity transmission system has not increased as previously expected. There is no urgent need for a large capacity transmission system such as the waveguide system except in England where the construction of a new mediam is required by the early 1980's.

Not only waveguide systems but also optical fiber transmission systems have been studied for a large capacity transmission system and remarkable progress has been made in just a few years. The development status of the optical fiber transmission system is still far away from the actual use, but the advantages are expected to be greater than those of waveguide systems in the fully developed stage. In such circumstances, waveguide engineers have started to wonder whether waveguide systems can remain as the best transmission system in the future when optical fiber transmission systems become available.

When we consider the techniques that have been established in different countries, we can find many differences from country to country even though they were concerned with the simple and particular property of TE_{01} mode circular waveguide. Waveguide design,

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TABLE 1 COMPARISON OF MILLIMETER WAVEGUIDE TRANSMISSION SYSTEM

	U.S.A.(BTL)	U.K. (BPO)	FRANCE (CNET)	WEST GERMANY (FIZ)	ITALY(FVB)	JAPAN (NTT)	NRAO
Field Trial Waveguide Length Year of Construction	14km 1974-75	14.1km 1975	10km 15km 1971 1973	3km x 3 lines 1968-71		4.2km 18.5km 3.8km '66 to '67 '71 to '72 '75 to '76	
Waveguide Diameter	(2") ↓ 60mm	50mm	50mm → (60mm)*	70mm	50mm	51mm	60mm
Waveguide Type	Dielectric Lined (99%) Helix (1%)	Helix (100%)	Helix (100%)	Dielectric Lined Helix	(Imported)	Dielectric Lined (75%) Helix (25%)	Helix (100%)
Waveguide Jacket	Steel	Glass re-inforced plastic	Glass re-inforced plastic	Aluminum or Steel		Steel	Steel
Waveguide Joint	Flange Welding	G.R.P. Sleeve Epoxi Injection	Flange Clamp	Flange		Threaded Sleeve	Threaded Sleeve
r.m.s. tilts r.m.s. offsets	.2 mrad	.756 mrad 12.75 μm					.7-1.0 mrad
Protection Method Duct material	132mm ID steel duct	105mm ID steel duct	No protection	126mm ID PVC duct		150mm ID steel duct	No protection
Support	Spring load roller	Plastic sleeve				Plastic roller	
r.m.s. curvature	≑ 1/300(m^{-1})					about 500m	about 1,000m (in improved te[illegible] about 550m (in old technique)
Minimum Route Bend Radius	150 (m)	100 (m)				30 (m)	
Waveguide Components (except ones at stations)		18mm dielectric lined waveguide gas window	corner waveguide gas window			corner waveguide, 14mm flexible helix waveguide, expansion waveguide	

Note: * = future plan

	U.S.A. (BTL)	U.K. (BPO)	France (CNET)	West Germany (FTZ)	Italy (FVB)	Japan (NTT)	NRAO
System	WT 4 ↓ (WT 4A)*					W-40G(T)	
Frequency	40-110 GHz	32-90 (110)* GHz	30-60 (90)* GHz			43-87(120)* GHz	
Waveguide Loss (Field Test Results) 40 GHz 50 " 90 " 110 " Minimum loss	 1.00dB/km .75 " .55 " .75 " .50 "(at 80 GHz)	 2.2dB/km 1.8 " 2.4 " 3.0 "	 2.8dB/km (38 GHz) 4.0 "			 3.4dB/km 2.7 " 2.7 " 2.2 "(at 65 GHz)	
(Straight) 50 GHz Minimum loss	 .75dB/km .45 " (at 90 GHz)	 1.65dB/km 1.25 "(at 80 GHz)				 1.7dB/km 1.4 "(at 75 GHz)	
Repeater Span	45-50km	20-30km				15km	
Signal Format	274 Mb/s (DS-4,4032VC) 2-DCPSK ↓ (4-DCPSK)* 124 Systems	560 Mb/s 4 phase DPSK 64 Systems	580 Mb/s (7680VC) 4 phase-PSK 21 Systems	264 Mb/s ↓ 640 Mb/s 2 phase-PSK		800 Mb/s 4 phase PSK 28 Systems	
IF Frequency	1.37 GHz	1.4 GHz	1.45 GHz	1.254 GHz	3.6 GHz	1.7 GHz	
Transmission Method	Direct mod.	IF Mod → up conv.	IF Mod → up conv.	Direct mod.		IF Mod → up conv.	
Demodulation			differential detection			coherent detection	
Transmission Capacity	240,000	492,000	150,000			300,000	

1. Waveguide System in U.S.A. (Bell Telephone Laboratory)

A. Experimental Line

1) Route

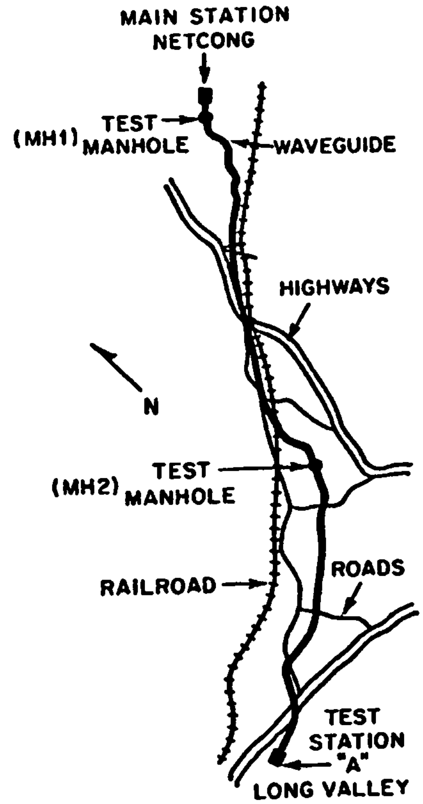


Figure 1. Field Evaluation Test (FET) Route

total length; 14km

plan bends; 22 (radii of less than 150 meters)

minimum allowable radius; 75m

mode filter; 18 pcs/14km (helix waveguide)

repeater span; 40~45km (expected)

2) Performance

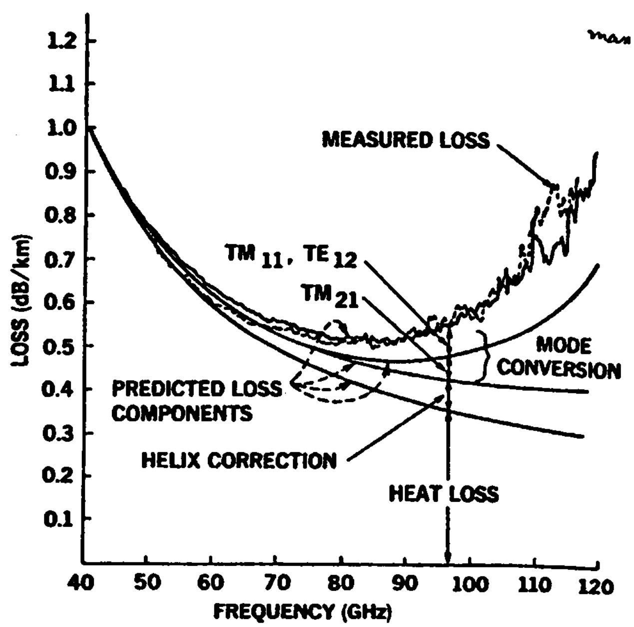


Figure 2. Computed and Measured Waveguide Loss for 14 km FET Route

B. Waveguide

1) Structure

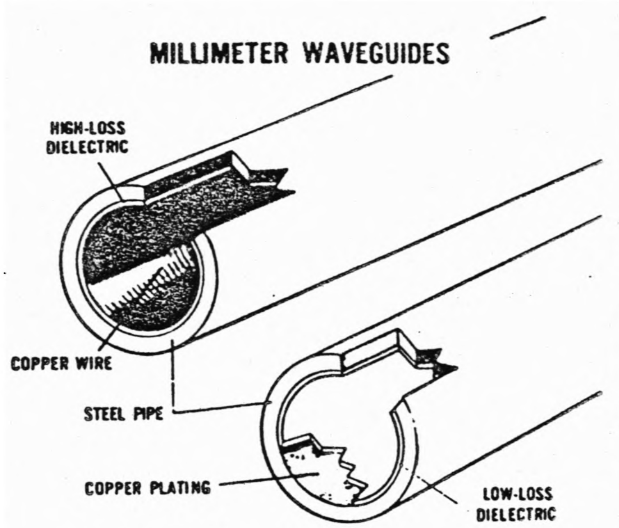


Fig. 3 - Millimeter Waveguides

60mm inner diameter

Waveguide line consists of

99% dielectric lined waveguide and (bottom)

1% helix waveguide (top)

Unit length:
8.7m with variation of 150mm max.

(Note: The dielectric lined waveguide used to be 90% and increased to 98% three years ago and increased to .)

2) Connection

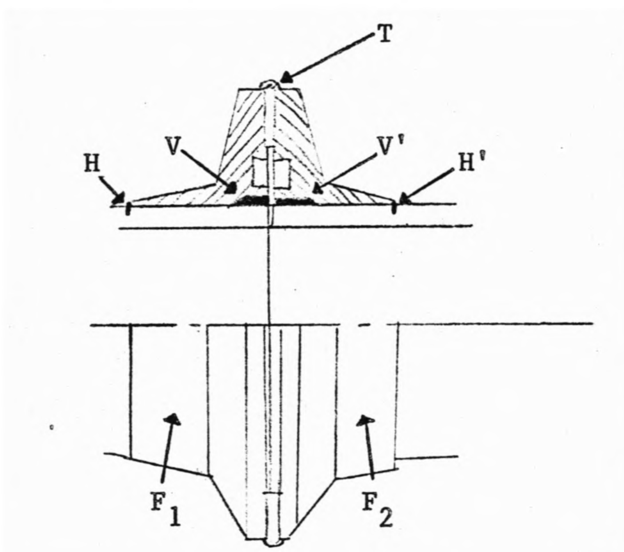


Fig. 4 - Waveguide Connection

V,V' H,H' electron beam welding (in the factory)

T ; T.I.G. welding (in the field)

performance

r.m.s. tilts	; .2mrad.
r.m.s. offsets	;
max. allowable stress	; 10,000 pounds
gas seal	; much better than any other technique

3) Attenuation in Straight Section

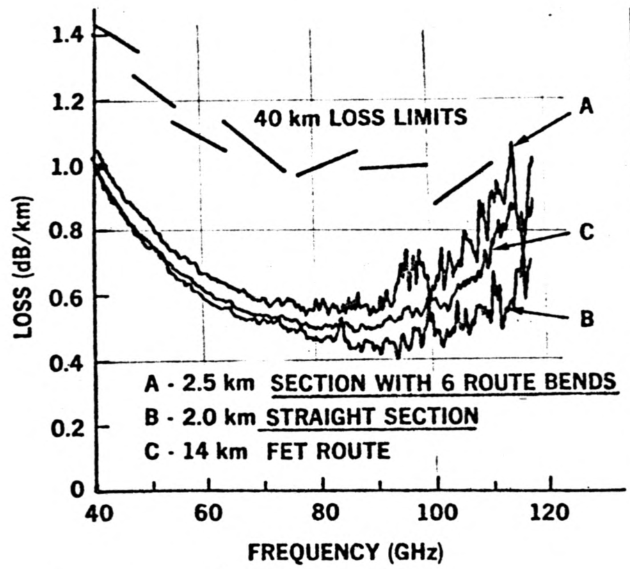


Figure 5. Waveguide Loss for Different Regions of WT4 FET

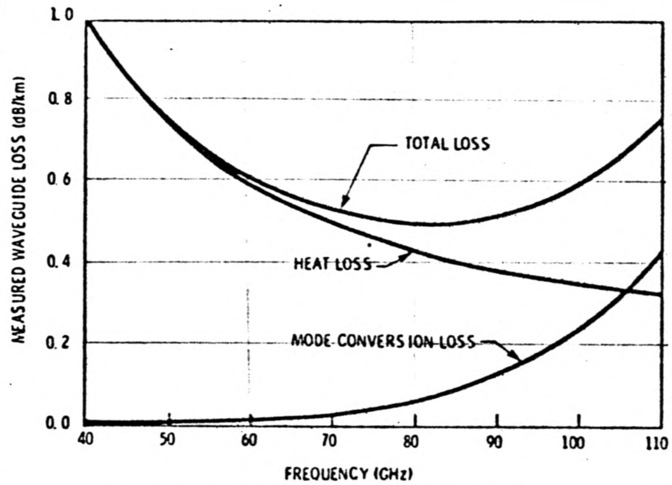


Fig. 6 - Measured Average Loss

4) Attenuation in Curved Section

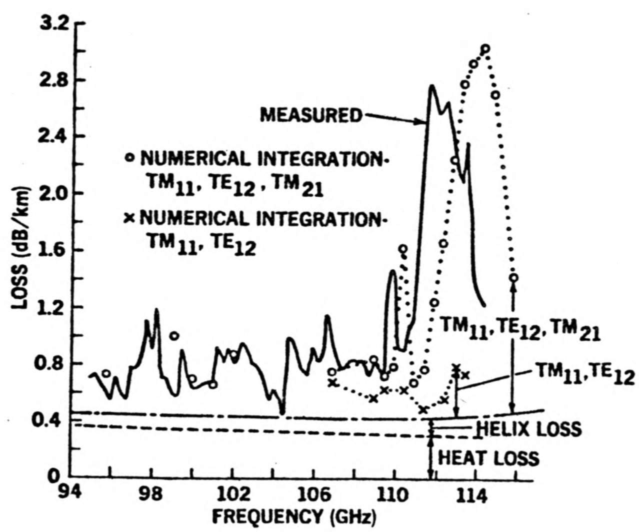


Figure 7. TE_{01} Loss Comparison for 720 m Section of FET Route

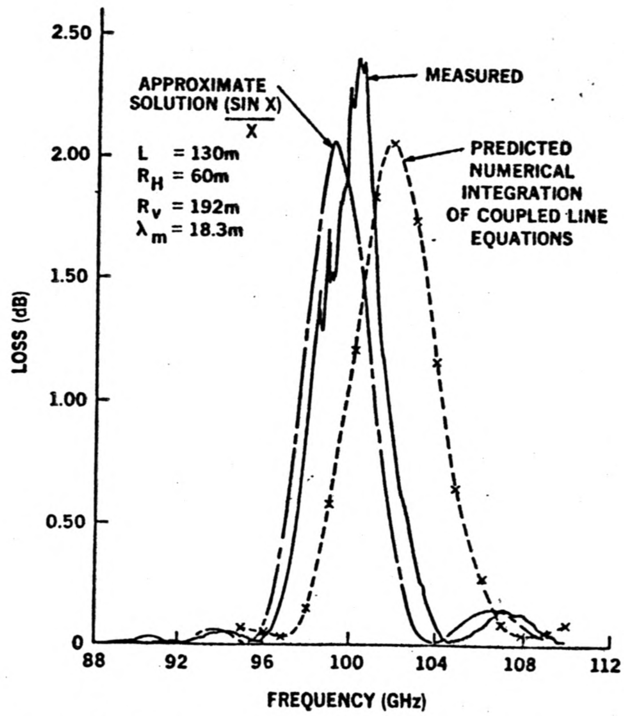


Figure 8. Measured and Predicted Losses for Experimental Route Bend

C. Installation

1) Sheath Installation

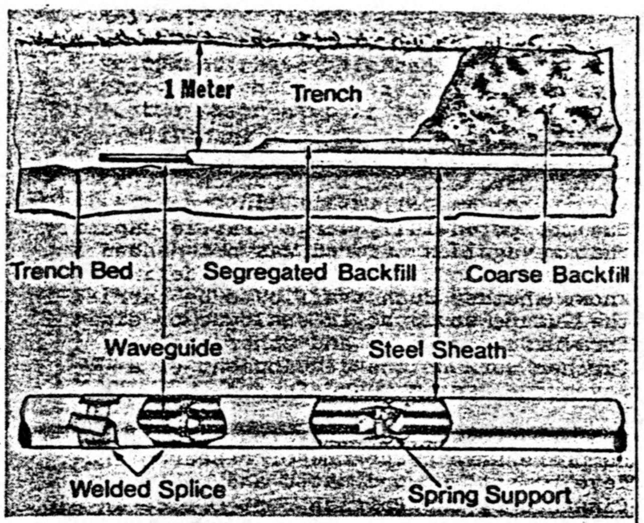


Figure 9 Installed Waveguide

Sheath	;	$5\frac{1}{2}$ inches ID steel tube
Sheath Connection	;	TIG welding
Depth	;	3.5 feet under ground
Trench Excavation	;	by wheel-type trenchers and backhoes
Trench Bottom	;	smooth enough to allow sheath to confirm elastically under its own weight
Others	;	minimum radius of 250 feet, no compaction around sheath

2) Supporting Systems

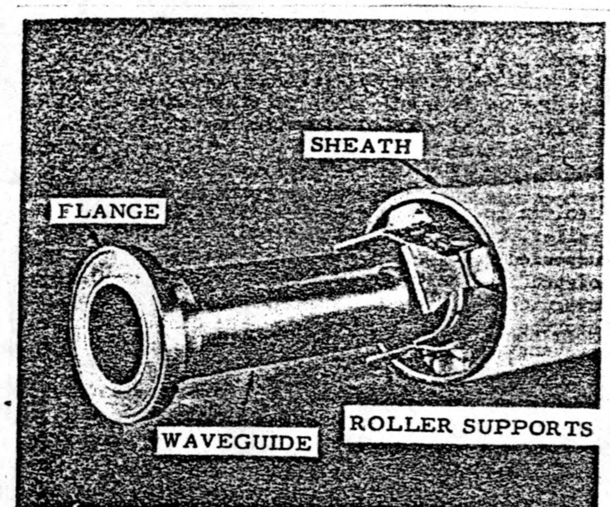


Figure 10 WT4 Sheathed Waveguide

Support Span	;	22 inches and randamized variation
Distributed Spring Constant	;	20 lbs/in.^{2}
Friction Coefficient	;	0.06 ~ 0.07

This support system was designed as follows:

1. Estimation of the range of sheath C.P.S.D. levels was made based on
   - 1.1 data obtained from sample sheath installations
   - 1.2 mathmatical modeling of the sheath response to soil loads and trench bottom irregularity
2. A continuous homogeneous elastic-type support was found to have the most desirable filtering attributes giving a transfer function like that of a low pass filter with a high cut-off rate.
3. Closely spaced discreet supports with spring-mounted rollers were designed for actual use. The behavior of supports were approximated by that of a continuous elastic foundation. (See Fig. 2)

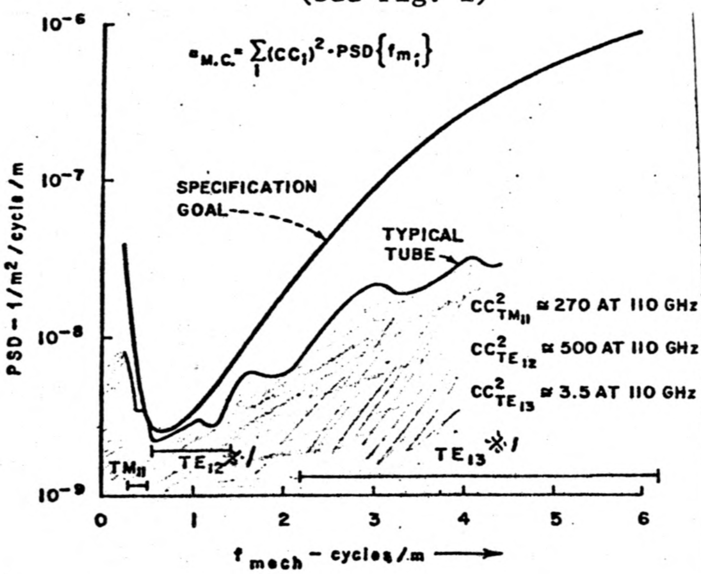


Fig. 11- Curvature PSD of Steel Tube for waveguide

Fig.1- These show beat frequency range from 40-110 GHz. Beat frequency is given in the following formula.

$\ell_b = \frac{2\pi}{\Delta\beta}$, $\Delta\beta$; the difference in phase velocity between TE_{01} and spurious mode.

In this range, loss increase becomes large, so P.S.D. must be small especially to the modes that have a large coupling coefficient as TE12.

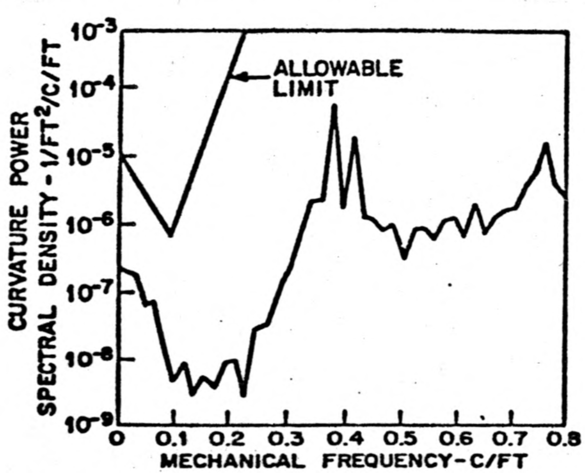


Fig 12- Sheath Manufacturing-Curvature Specification

Fig.2- The r.m.s. radius can be got as follows

$$R_{r.m.s.} = \frac{1}{\sqrt{2\int_0^\infty PDS(f_2)\,dfm}}$$

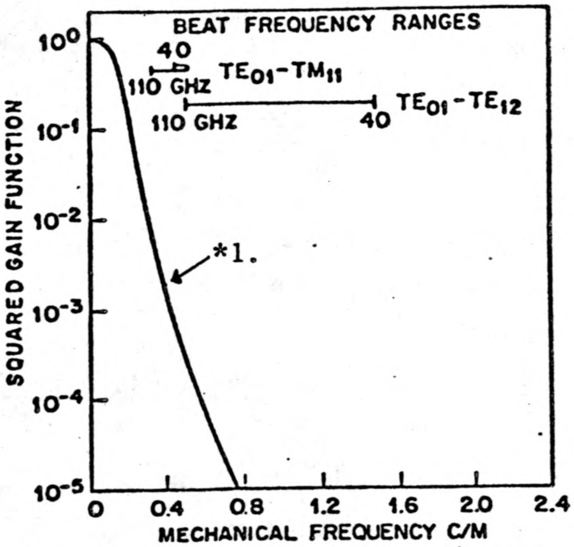


Fig 13 Squared Support-System Gain Function

*1. This response removes the small period of bend in waveguide even though the sheath has some bends.

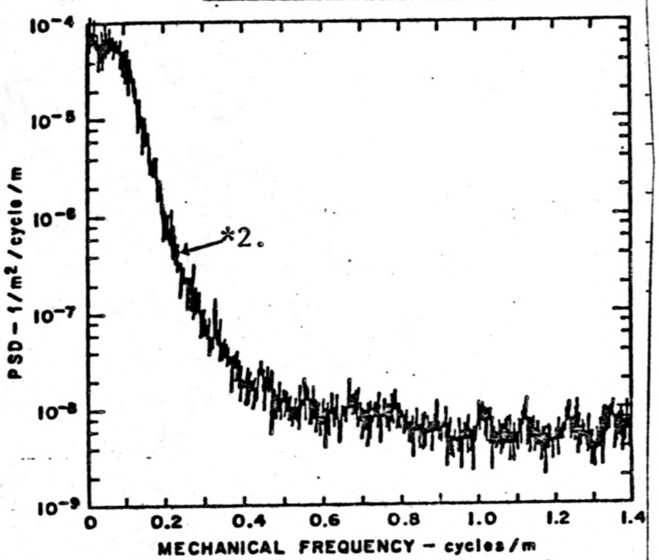


Figure 14 Curvature PSD of Installed Waveguide

*2. PSD response is coming down quickly with the increase of mechanical frequency. This is the main reason why they obtain an excellent electrical performance, even though R_{rms} is only 300m.

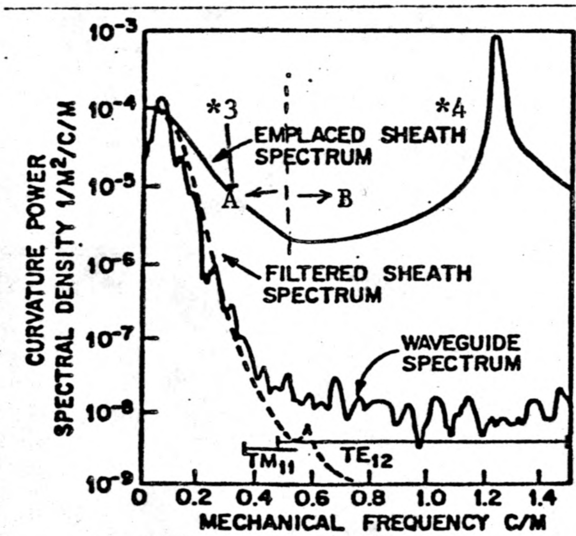


Fig. 15 Emplaced Sheath and Waveguide Curvature Spectra

*3. Curve in area "A" is based on mathematical modeling, "B" was obtained from sample installation.

*4. Waveguide directly installed under ground seems to have similar PSD response to that of sheath.

3) <u>Waveguide Insertion</u>

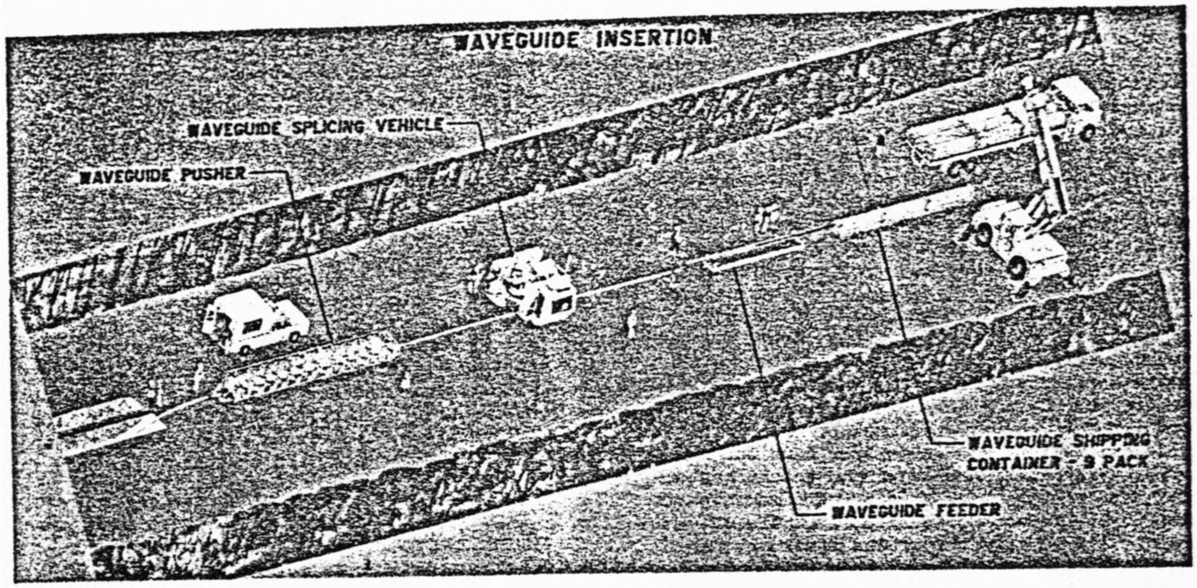


Figure 16 Experimental Waveguide Insertion System

Pushing Force Maximum	; 10,000 pounds
Friction Coefficient (during pushing)	; 0.06-0.07
Pushing Length Maximum	; greater than 4.8 (F.E.T. 14km/8 pushes with maximum 2.5km)
Pushing Speed	; 2 ft./sec.
Overall Insertion Speed	; 3-5 min./section(9m) ≒ 100-180m/hour
Required Weather Condition	; none
Cost	; 3% of the total mediam cost

D. Gas Maintenance System

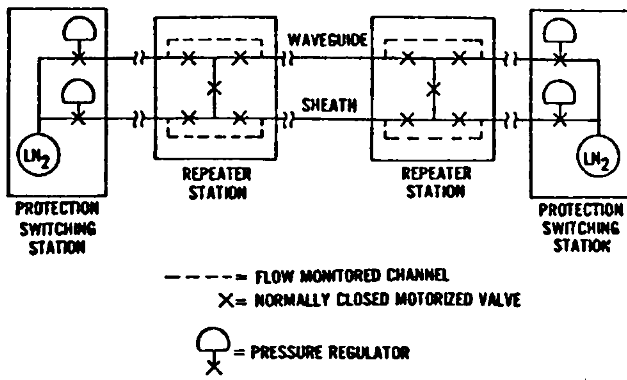


Figure 17 Nitrogen System Schematic

pressure	
1) in waveguide	;10psi
2) in annulus between waveguide and sheath	;8psi
gas source	;liquid nitrogen (capacity 900 gallons)
supplying speed	;$1m^3$/min (150 miles/1.5days)
supplying station	;every 600 miles
reliability objective	;no more than trouble per 1000 mile year

1) Leak Localization

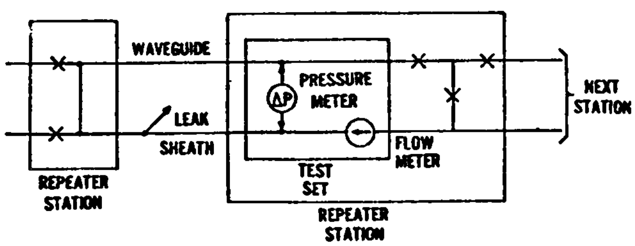
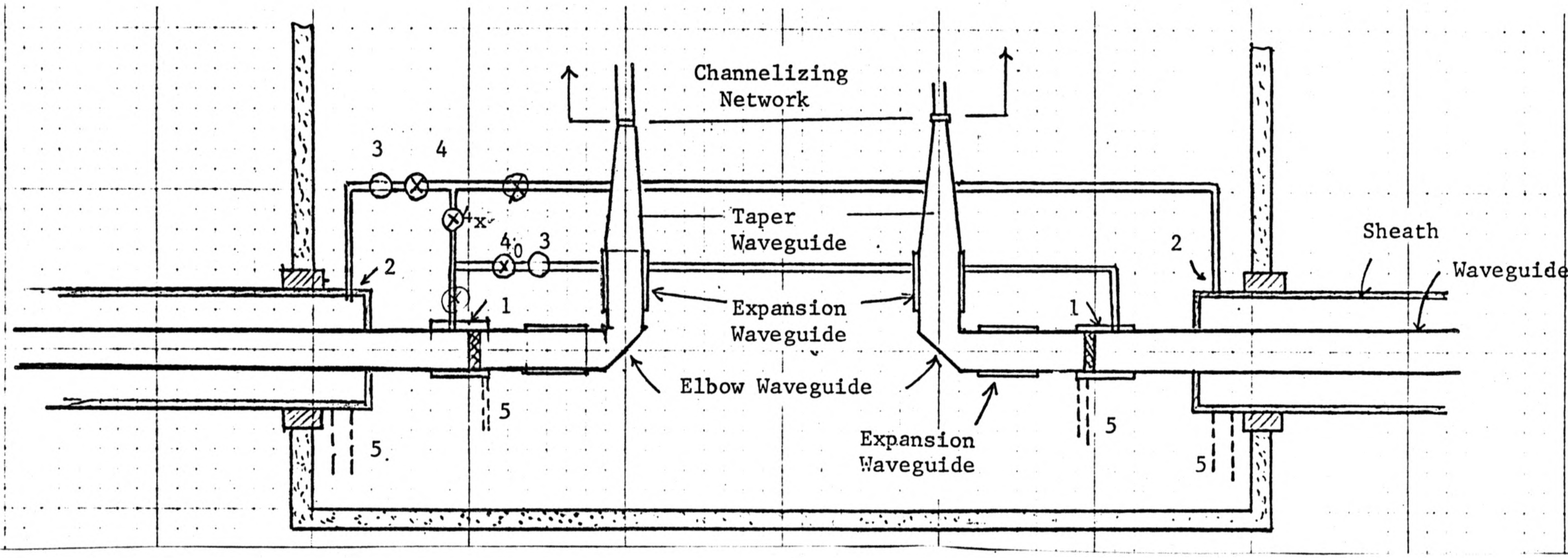


Figure 18 Leak Localization Technique

1. Sectionalization by flow monitors → one repeater span
2. Localization by flow division technique → within .25 miles. (see left-hand side drawings)
3. Pinpointing by tracer gas technique

Figure 19 Details in Repeater Station



Gas Equipment

1. Waveguide Window
2. N_2 Gas Manifold
3. Flow Meter

$4_x, 4_0$. Gas Valves

5. Exhausting pipe

Note

1. Refer to Figure for detail in waveguide window
2. Pipe connection is not always correct in detail because it is added based on the discussion with people from B.T.L.

2) Waveguide Gas Window

a. Configuration

Dielectric material; foamed plastic (especially developed under instruction of B.T.L.)

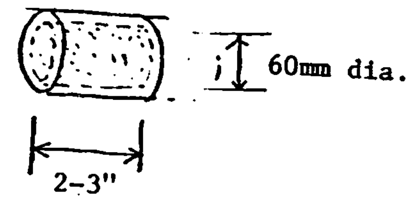


Fig. 20 Waveguide Gas Window

Dielectric const. (ε); 1.03

Waveguide inner dia. ; 60.0mm

Length of dielectric ; 2 - 3"

b. Performance

Return loss; greater than 30dB (30 -110 GHz)

Insertion loss ; 0.15dB

Gas seal ; no failure more than 4 years under 4.0 kg/cm^2 pressure

c. Discussion

TE_{02} mode generation is unknown

The length of dielectric (ℓ) is not important for return loss performance

d. Note

TE_{02} mode generation should be checked out

Return loss must be increased by 5 - 10dB for VLA waveguide system

E. Band and Channel Dropping Filters

1) Layout

Electrical and physical schematic is shown in Figure 23.

a. This network has six band-splitting filters. Each band-splitting filter consists of two 3dB beam-splitter coupler and two corner waveguides and several circular taper waveguides. (refer to Fig. 25)

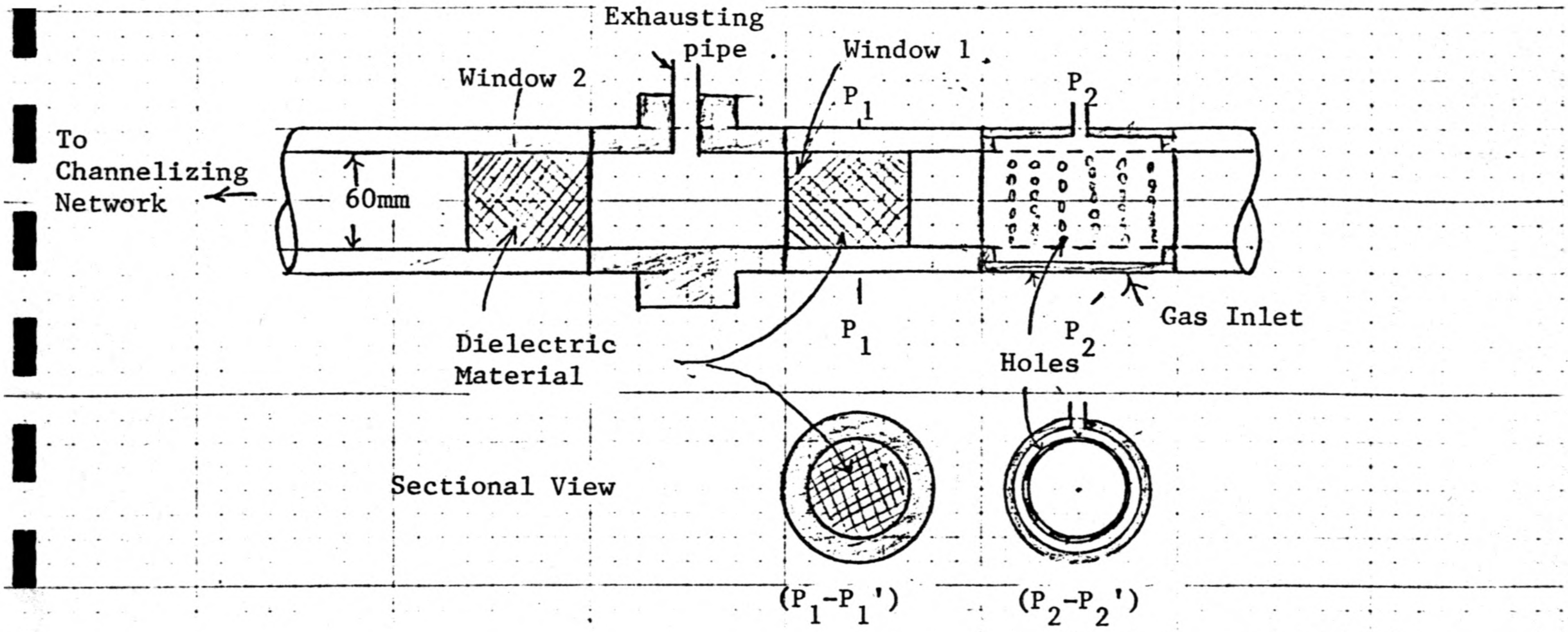
b. This network separates individual channel of 475 MHz bandwidth by using resonant cavity.

(Note:

beam-splitter: We are developing these as couplers in the VLA.

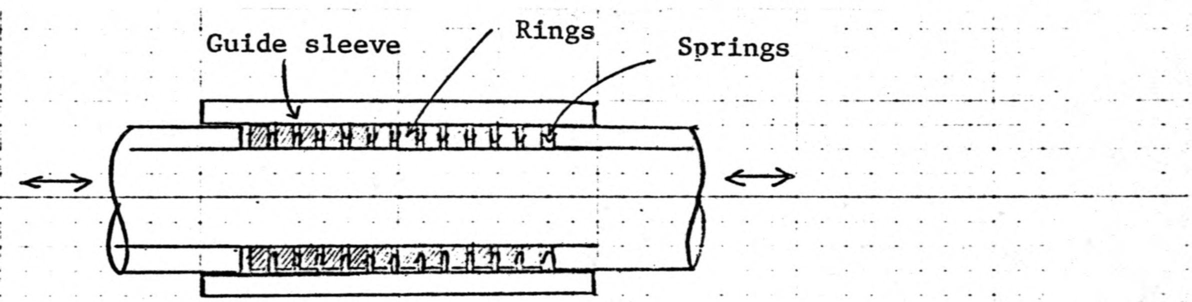
resonant cavity: This limits the bandwidth. Filter network in VLA is composed of several band-splitting filters. Each filter consist of two 3dB directional coupler and two cut-off tapers having the rectangular or semicircular cross section. Refer to Fig. 26.)

Fig. 21 Waveguide Window and Gas Inlet



Note: If window 1 breaks, nitrogen gas inside waveguide is removed from exhausting pipe to prevent the damage from high pressure in channelizing network and other equipment.

Fig. 22 Expansion Joint



2) Performance

a. Typical performance is shown in Fig. 24

b. The loss of band-splitting filter is almost 1.0dB. (The diameter of hybrid is 51.0mm)

c. TE_{21} mode generation from beam-splitter coupler deteriorates performance in band-splitting filter, so TE_{21} mode filters (helix waveguides) are required.

d. Delay drift in filter network is less than .2 - .3 nsec.

(Note:

A. Fig. 24 looks better than VLA filter network regarding fine variation (B.T.L. - less than 0.2dB, less than 0.5dB in 50 MHz band)

B. Regarding (c.), in the VLA filter network, the major source of deterioration seems to be 3dB directional couplers that have distribution coupling elements.

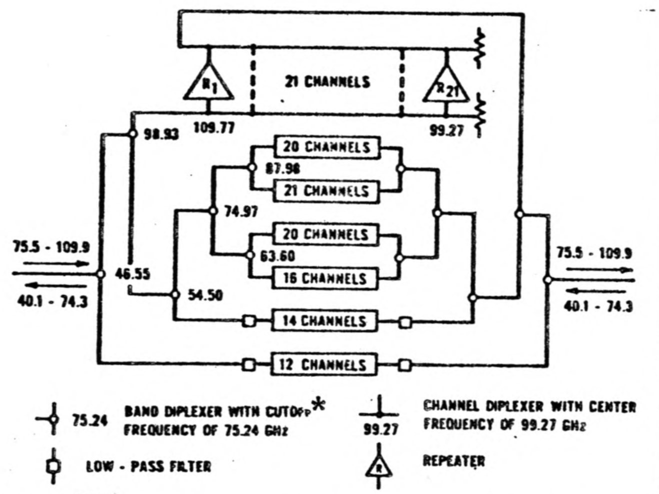


Fig. 23 - Band and Channel Dropping Filters

*It consists of two beam-splitter couplers and two cut-off tapers. (See Fig. 25)

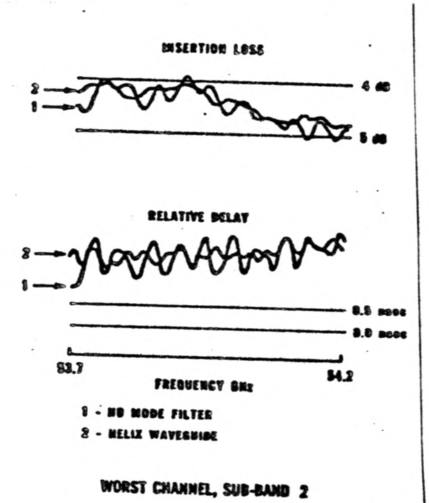


Fig. 24 Band & Channel Dropping Filters Performance

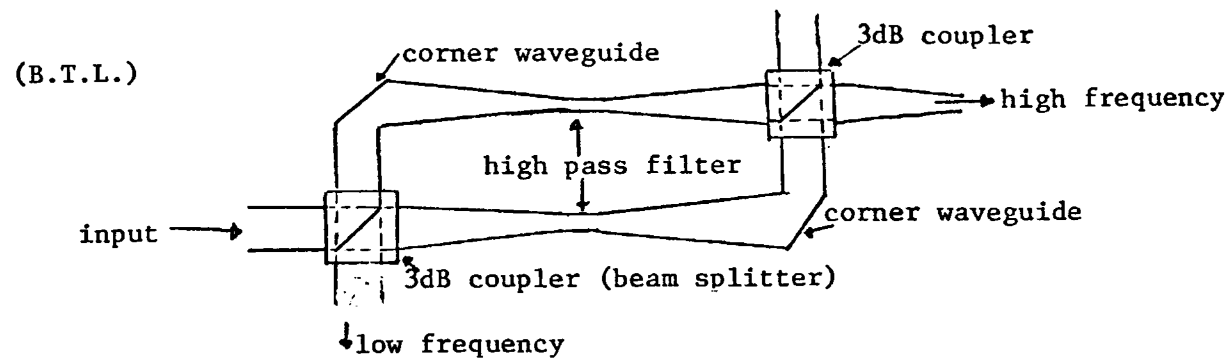
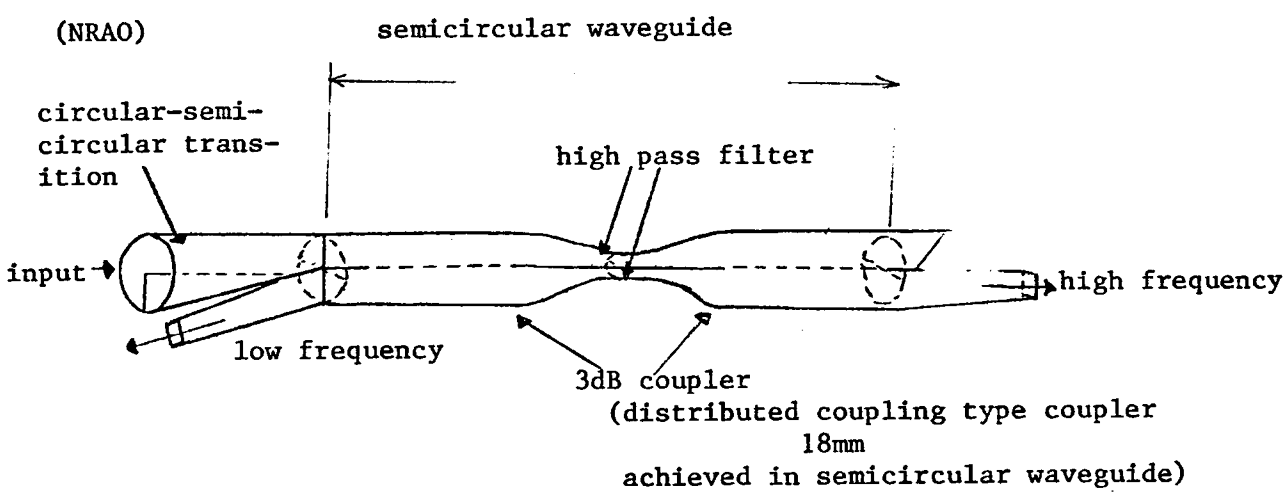


Fig. 25 Band-Splitting Filter of the B.T.L.



Some part is achieved in rectangular waveguide instead of semicircular waveguide.

Fig. 26 Band-Splitting Filter of the NRAO

3) Some Other Information

a. They are using 3dB beam-splitter coupler to measure the return loss in circular port in B.T.L. (Refer to "Return Loss Measurement")

b. The holding method of dielectric in beam-splitter coupler is below. (It could be useful for our coupler design.)

*1. No offset between waveguides 1 and 2.
*2. Boundary position between dielectric material is not critical.

c. They have never tried other angle hybrid rather than right-angle hybrid.

d. They are using 2" inner diameter in hybrid, because the the diameter of main waveguide used to be 2" dia. several years ago and these hybrids were developed at that time.

F. Measurement Technique

1) Waveguide Loss

The electrical transmission measurements are accomplished by an automatic pulse reflection test set. This test has the following features.

a. oscillator ; Voltage controlled back wave oscillator

b. frequency range ; 33-50 GHz, 50-75 GHz, 75-115 GHz

c. frequency scan ; 10 GHz

d. frequency step ; 50 MHz

e. pulse width ; 100 nsec

f. dynamic range ; 60dB

g. measurement error ; Less than 1%

h. distance between test set and shutter; 600m

2) Mechanical Measurement

A gauge termed a "Long Distance Mouse" has been developed and is used to measure curvature of waveguide axis and inner diameter for the entire route. It has the following features.

a. mouse configuration; shown below (self-running)

b. spacing between reference wheels ; 1 foot

c. data sampling ; every 1 cm

d. data transmission ; 80 GHz inpatt diode transmitter is used to send digital signal at 8 K band rate.

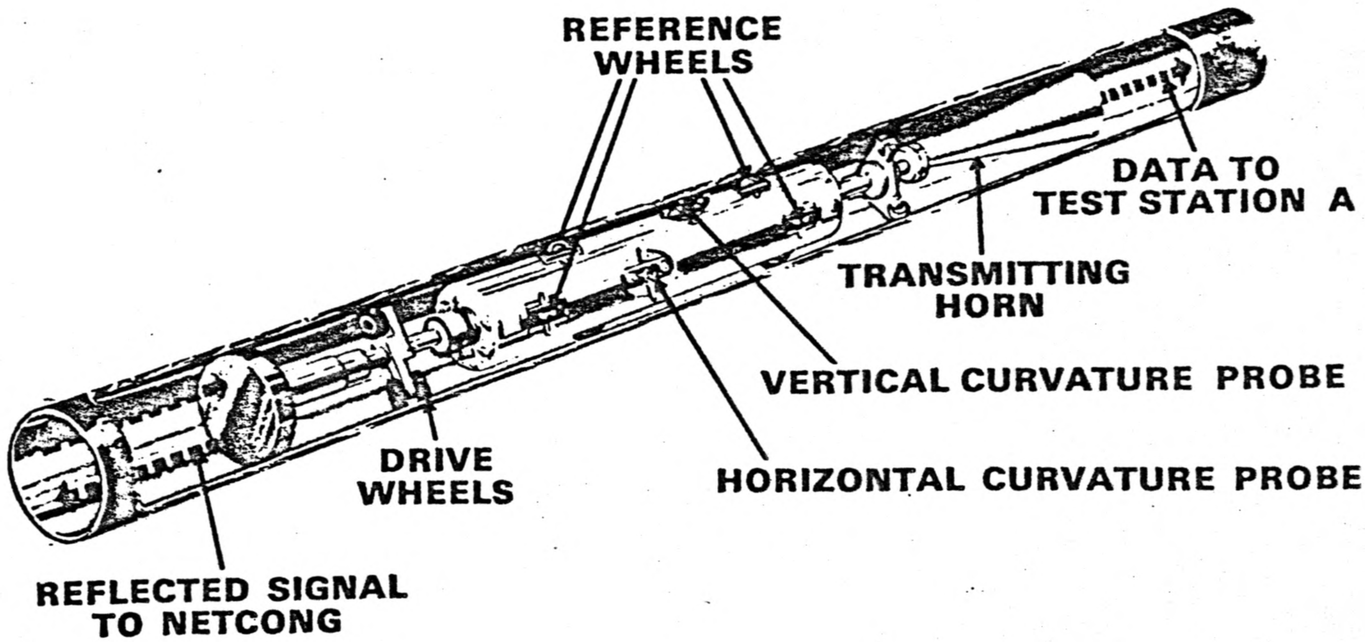


Figure 27 WT4 Long Distance Mouse

3) Return Loss Measurement in Circular Port of Components

3dB coupling beam-splitter coupler of 2" diameter is used as directional coupler in B.T.L. to measure the return loss in circular port.

Comments

1. According to Mr. H. Hirotani from Hitachi, 3dB beam-splitter coupler has lower limit in frequency that is determined by the diameter. To get more than 35dB directivity over 28 GHz range, the diameter must be greater than 80mm.

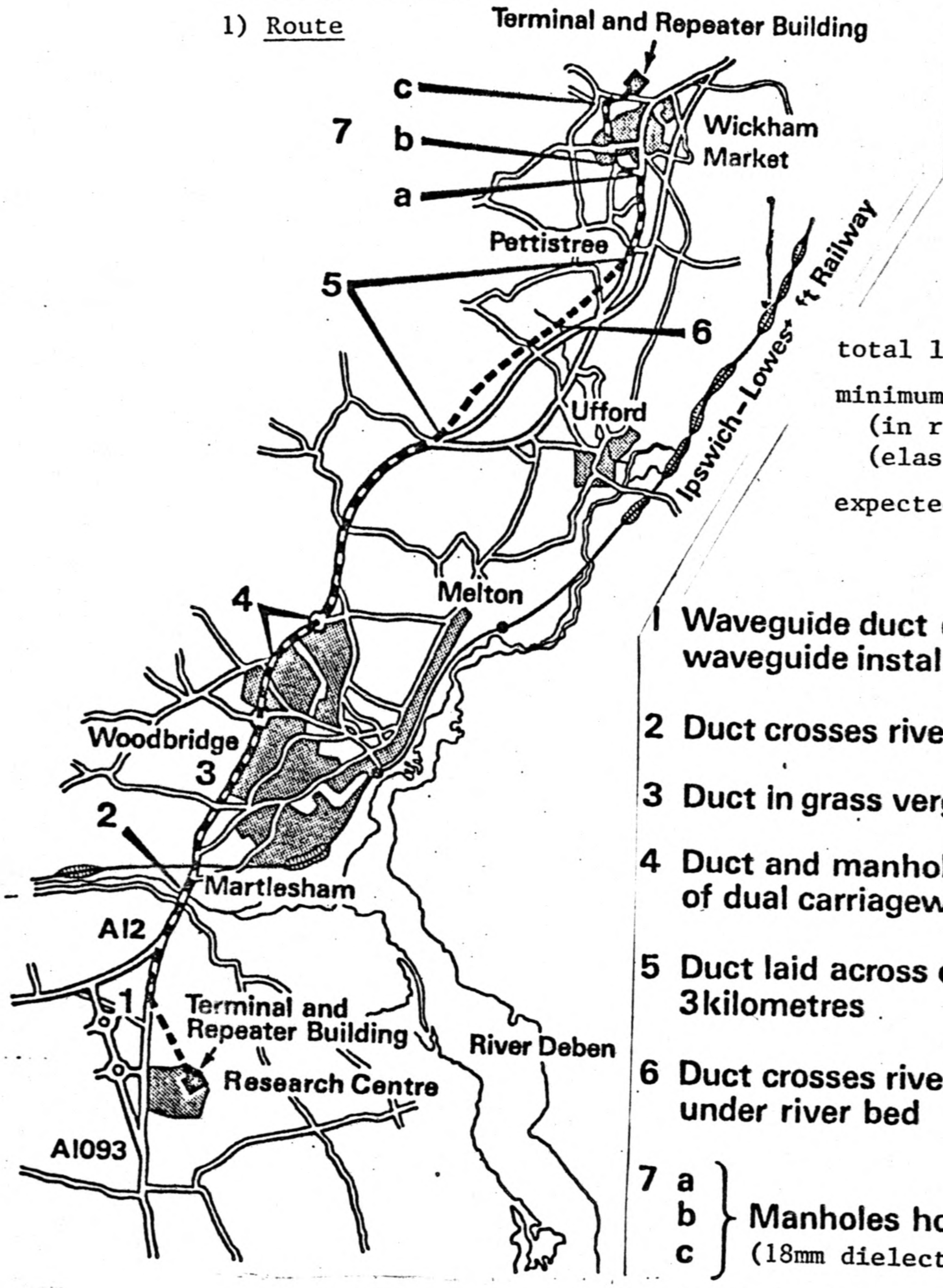
For this reason they developed circular-circular directional coupler to measure the return loss of signal distributor in Hitachi.

2. For evaluation of couplers in VLA waveguide system, we need a measurement technique by which we can measure the return loss of greater than 35dB in 27-53 GHz. It is necessary to develop new techniques.

2. Waveguide System In The United Kingdom (British Post Office)

A. Experimental Line

1) Route



total length; 14.1km

minimum bneding radius; 100m
(in route bend)
(elastic limit of waveguide; 60m)

expected repeater span; 20 ∿ 30km

Figure 28. Experimental Line Route

2) Performance

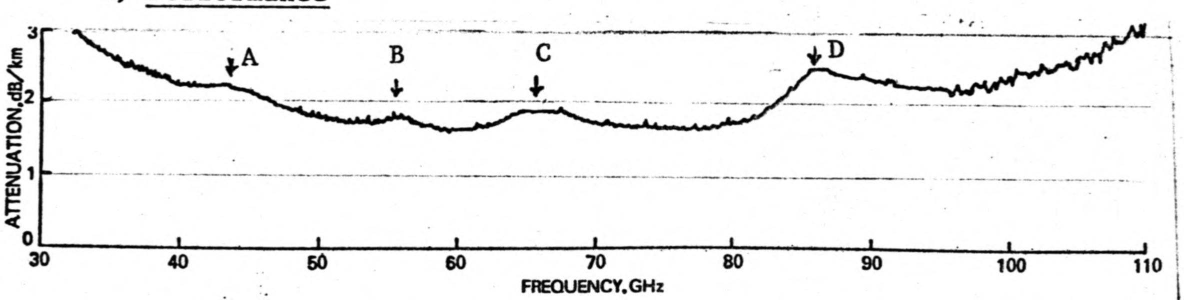
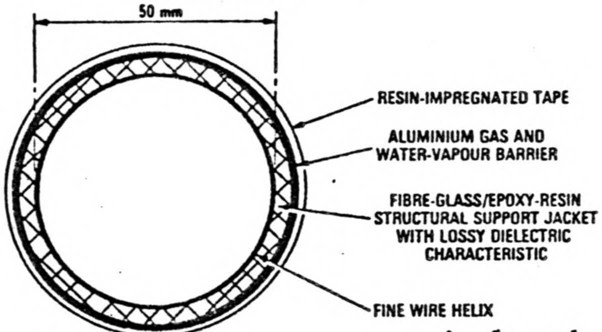


FIG.29 OVERALL ATTENUATION OF 14.1 km FIELD TRIAL ROUTE INCLUDING THREE SHARP 90° BENDS

* Those peaks were caused by route bends (minimum radius; 100m) and sharp bends achieved by 18mm dielectric lined waveguide.

B. Waveguide

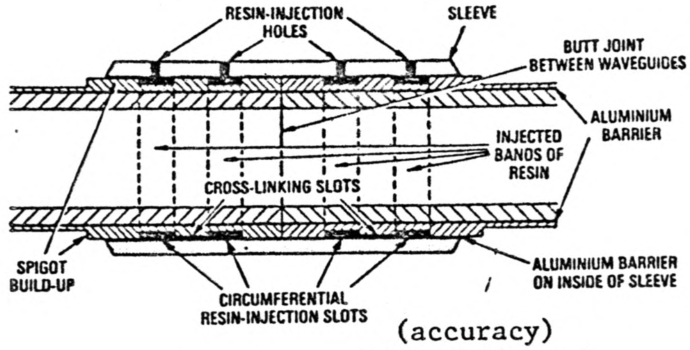
1) Structure



unit length = 3m.

Not to scale

FIG. 30 Cross-section of helix waveguide



(accuracy)
tilt .756 mrad.
offset 12.75μm

FIG. 31 Waveguide joint

2) Attenuation in a Straight Line

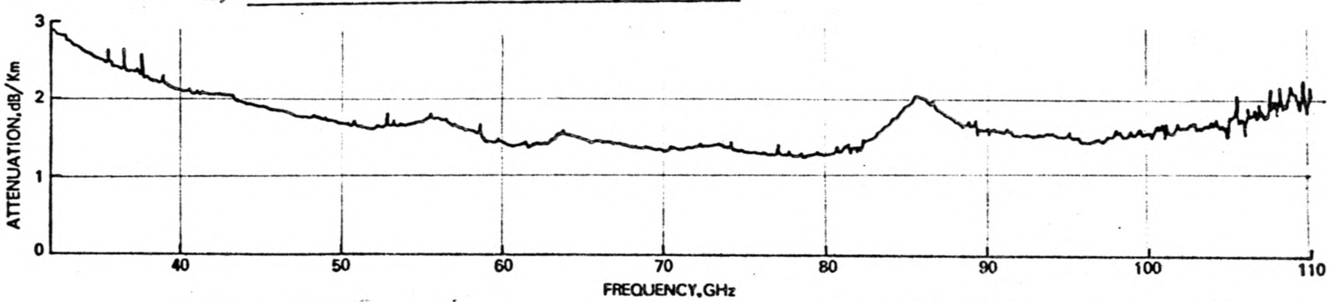


FIG. 32 ATTENUATION OF WAVEGUIDE IN A STRAIGHT SECTION OF ROUTE (in duct)

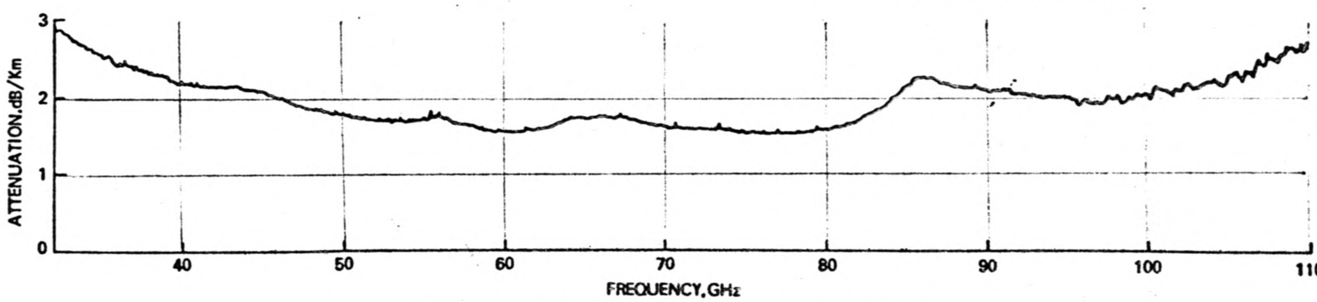


FIG. 33 ATTENUATION OF WAVEGUIDE IN 12 Km OF ROUTE

3) Attenuation in a Bend

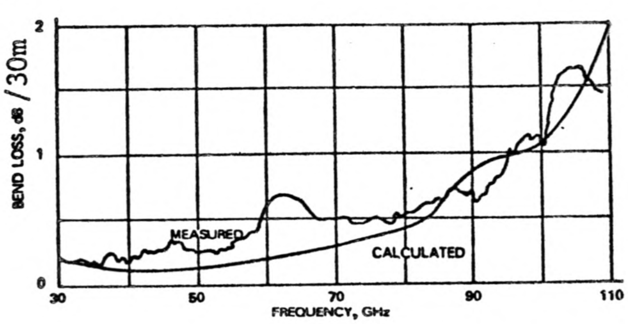


FIG. 34 MEASURED AND CALCULATED BEND LOSS COMPARED.
HELIX - TO - SCREEN SPACING 0.6 mm.
BEND LENGTH 1 RADIAN, RADIUS 30 m.

(in a new design)

C. Waveguide Protection and Installation

1) Protection

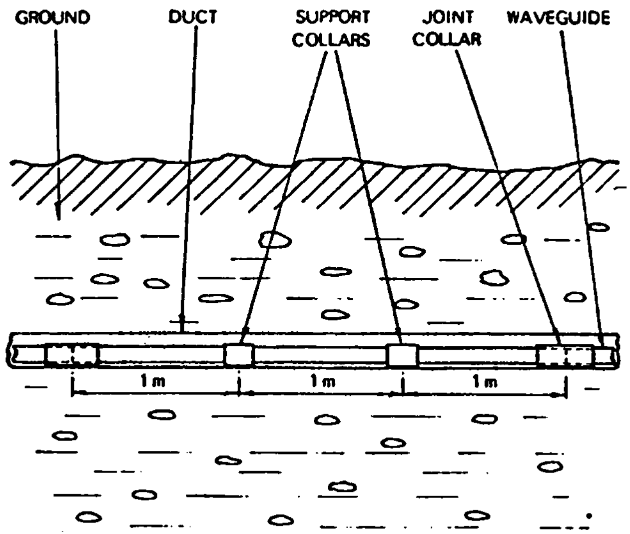
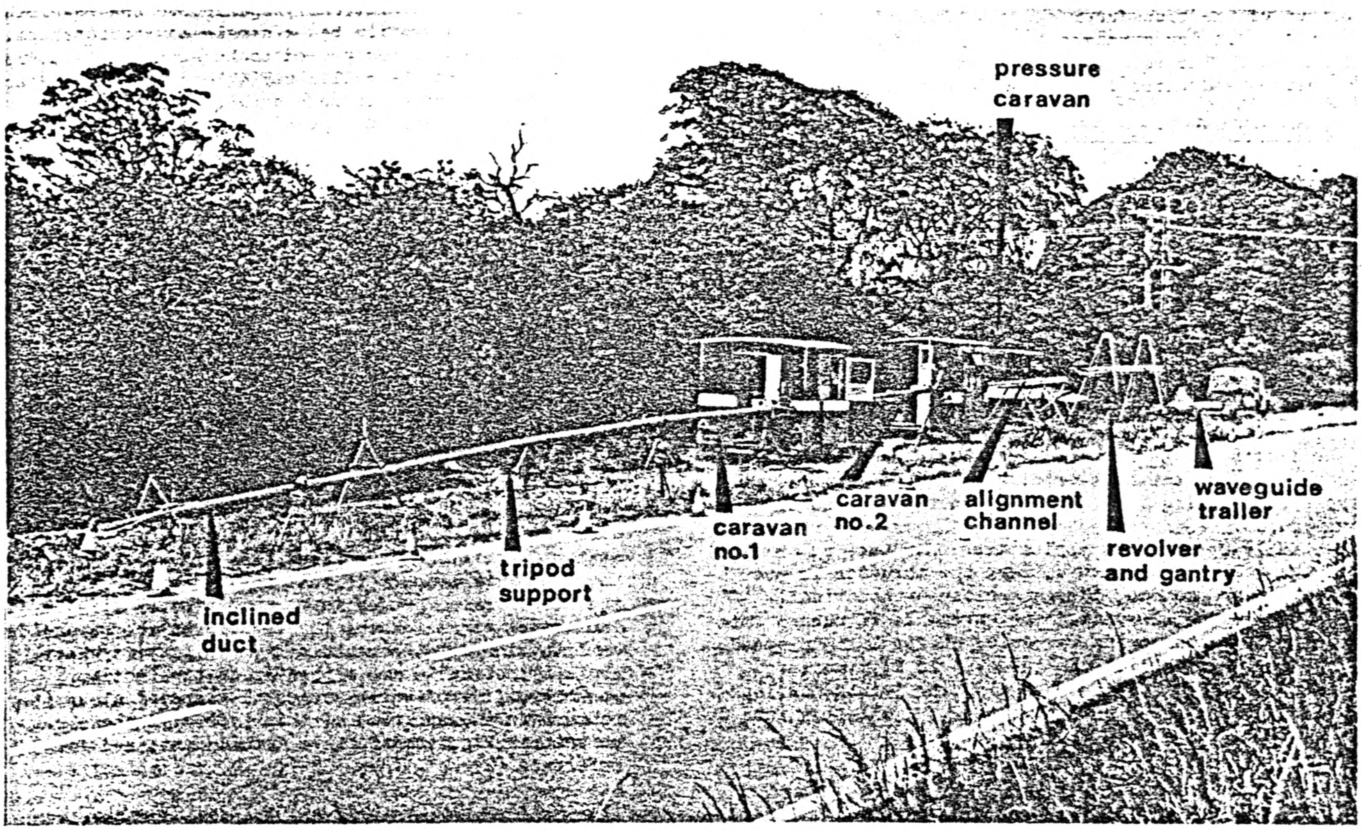


FIG. 35 WAVEGUIDE IN DUCT

duct dimension; 105mm ID
116mm OD

rms curvature of duct; $1/735\ m^{-1}$ (in vertical)
$1/960\ m^{-1}$ (in horizontal)

2) Installation



Note: Waveguide is pushed into the pre-installed duct.

Figure 36 Waveguide Installation equipment layout

connection speed; 30 min/one joint
installation speed; 14.2 km/28 weeks (≑ 507m/week, eight man team)
pushing force; 2500 kg/km
(friction coefficient between waveguide and duct ≑ .6)
maximum pushing length; .87km
(achieved typical data in construction of experimental line)

D. Waveguide Maintenance

1) Pressurization

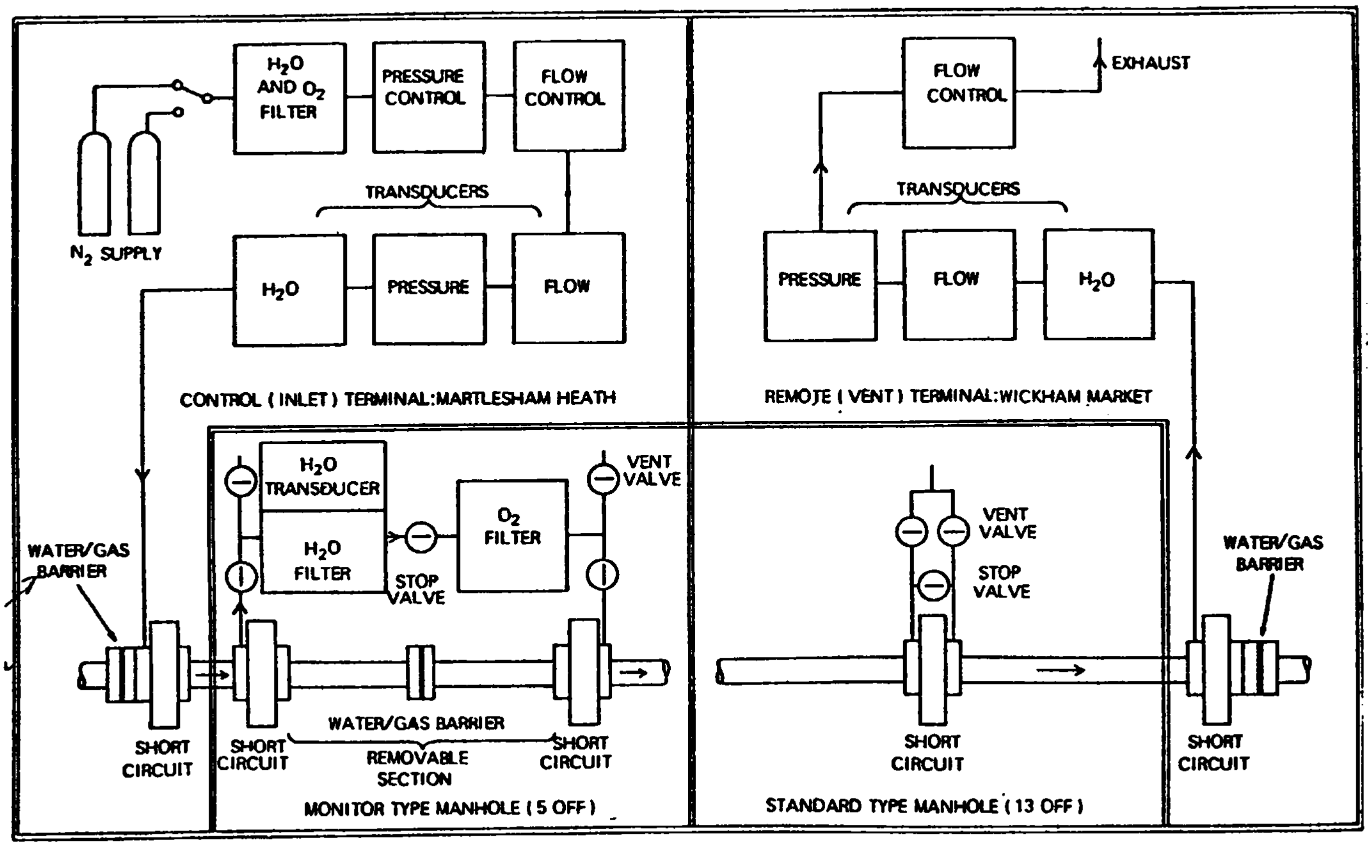


Figure 37 Simplified block diagram of the waveguide pressurization system.

2) Specifications

oxygen in exhaust gas; less than 1 ppm

water vapor in exhaust gas; less than 200 ppm/km

leakage from a joint; less than $6mm^3/min$ under $10lbs/in^2$

E. <u>Other Information</u>

1) <u>Reduced Diameter Dielectric Lined Waveguide</u>

18mm diameter dielectric lined waveguide has been studied as a component covering the sharp bends in B.P.O., while limited numbers of miter corner waveguides have been considered in B.T.W. and the combination of miter corner waveguide and semiflexible helix waveguide has been considered in N.T.T. for the same purpose.

It has the configuration shown in Fig. 5-1. The design criteria and expected performances had been shown by H.G. Unger. The problem in achieving a good performance used to be how to bend such a waveguide to the specified profile curve (not a uniform radius curve). But this has been solved by improvement of bending technique, and this waveguide has become promising in the B.P.O. waveguide system. It offers less than .2dB loss in a 90^{o} bend of about 1.3m equivalent radius in 30 ∿ 110 GHz except several loss peaks.

The loss peak mechanism that has been clarified is expected to be reduced or shifted to unused frequency bands.

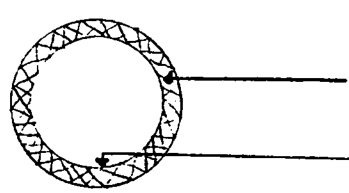


Figure 38 Reduced Diameter Dielectric Lined Waveguide

<u>Comments</u> This technique might be applicable to antenna waveguide instead of semiflexible helix waveguide and it might be possible to get less than 2dB. (At present 1.5dB ∿ 2.0dB in Furukawa flexible waveguides, 4 ∿ 5dB in Fujikura flexible waveguides.) The following will be necessary to develop this kind of waveguide useful for the VLA waveguide system.

C.R. South, "Intentional Sharp Bends in Reduced Diameter Circular Waveguide", IEE Conference on Millimetric Waveguide Systems, pp, 64-67, Nov. 1976

Loss of manufactured 90° Bend and Tapers

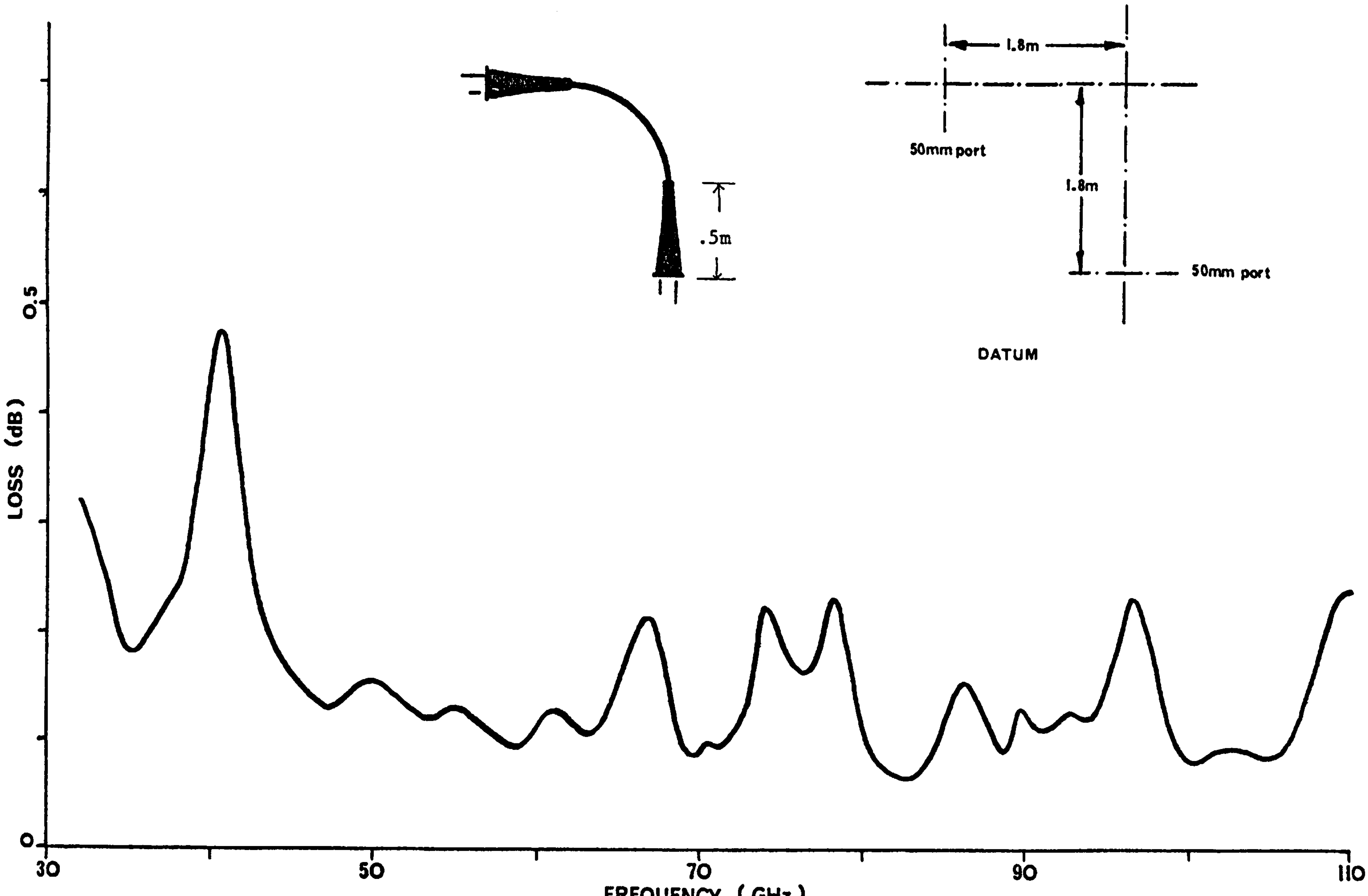


Figure 39

1. Design of waveguide of 20mm diameter in 27 ~ 53 GHz

   (thickness of dielectric material)

2. Design of curve profile applicable to antenna

3. Study of installation

When the design is available, the company in England could try-manufacture. Even if it could be developed, installation might remain as a problem. The important thing in installation is to keep pre-bent configuration within elastic limit of copper pipe. The limit could be considered around $\pm 5^{\circ}$ in the offset angle from the specified one in 90° bend. (This information is from a discussion with C.R. Smith.)

2) Duct Installation Technique

They studied the installation technique of ducts in which they later pushed waveguides in. The duct has a 105mm ID and a 5.5mm thickness. First they placed it on the supports with 1m interval and put back the evacuated soil without any compaction of the soil around the waveguide. They found the straightness deteriorated after backfilling shown below. After they found the compaction of the soil around the waveguide was important, the deterioration caused by backfilling has become smaller.

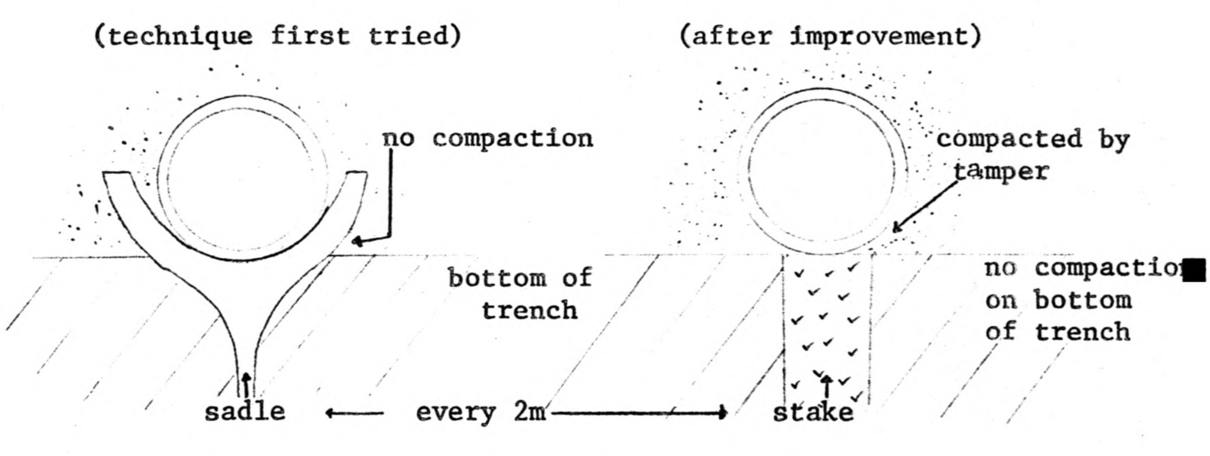


Figure 40. Installation Techniques

The Change of r.m.s. Radius Before and After Backfilling

	(The First Technique)		(After Improvement)	
	Before	After	Before	After
Horizontal	1,206	520	872	680
Vertical	250	258	536	402

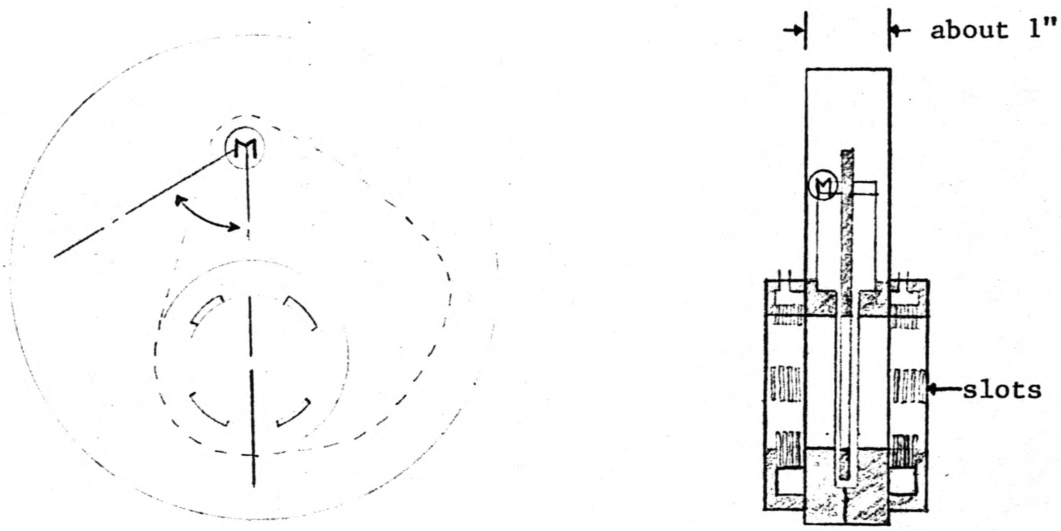
(Unit; m)

The deterioration of straightness of duct three years after installation, was immeasurable. (This information came from a discussion with G. Morrow.)

3) Gas System Components

a. Short Circuits

In B.P.O. test line, many short circuits were installed. It acts as a shutter or short at the time of loss measurements and as a gas valve when depressurization is required in one part of the line. It is driven electrically and has the following configuration.



slots; about .004" wide
about 1" long in circumferential direction
in several rows in axial direction
in 4 places in circumferential direction

Figure 41. Short Circuits

b. Features

4) Commercial Line in the Future

The British Post Office decided to install the 132km waveguide between Bristol and Reading by 1982. This is the first decision to use waveguide in actual commercial service, while B.T.L. and N.T.T. are pending their decision because of recession and insufficient demand, even though they have the needed technique. (This information was obtained from presentations given by people from the B.P.O. Research Center.)

3. Waveguide System in Japan (Nippon Telephone and Telegraph Co.)

A. Experimental Line

1) Route

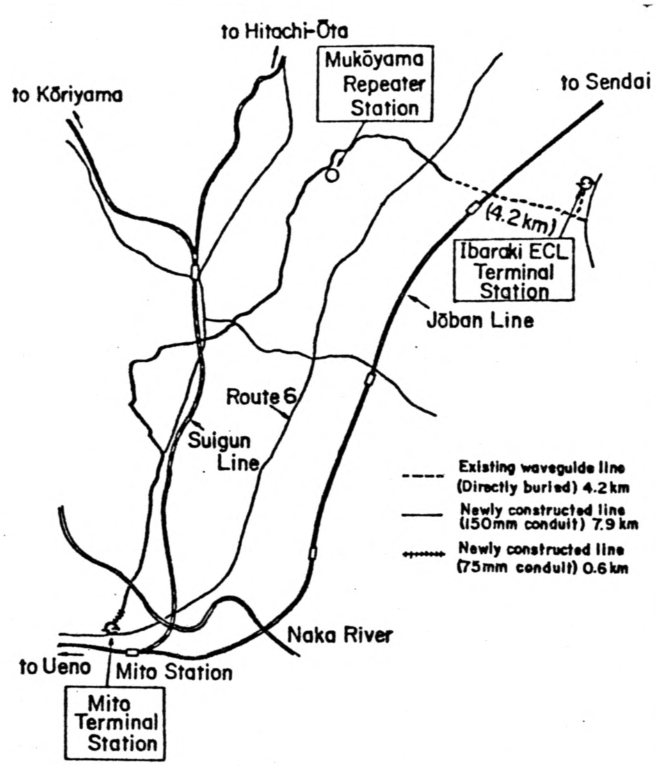


Fig.42. The route map of the W-40G field trial link.

total length; 22.7km
- direct burial; 4.2km
- 51ϕWG in conduit; 17.9km
- 40ϕWG in conduit; .6km

minimum bending radius; 30m
expected repeater span; 15km
features: waveguide route is expected to be same as coaxial cables, so it will contain many bends

T. OUTLINE OF NEW EXPERIMENTAL WAVEGUIDE LINE

Waveguides	51 mmϕ, 4:1 Tandem hybrid waveguide	17.9 km
	40 mmϕ, All helix waveguide	0.6 km
	Corner waveguide Single	18 (10 in the station)
	〃 Double	12
	Telescopic waveguide	20
	20 mmϕ small dia flexible waveguide	4
Conduit	150 mmϕ steel pipe covered with asphalt, coller welded	17.9 km
	75 mmϕ cable conduit	0.6 km
Manhole	Large (length 6.3 m)	13
	Small (length 2.3 m)	33
Supervisory	Detecting dry air pressure in the conduit	
	Span	9
	Dry air pressure	0.55 kg/cm²
	Nitrogen pressure	0.7 kg/cm²

These are features of the Japanese Waveguide System

2) Performance

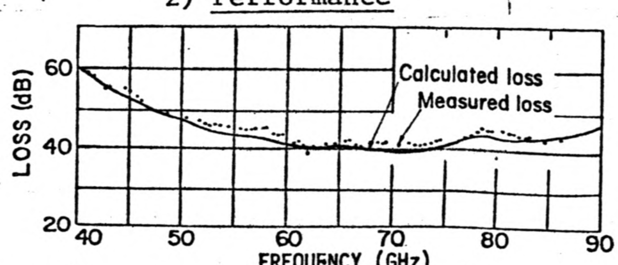


Fig. 43. Loss characteristic of the waveguide line laid in 150 mm I.D. steel conduit (17.88km)

B. Waveguides

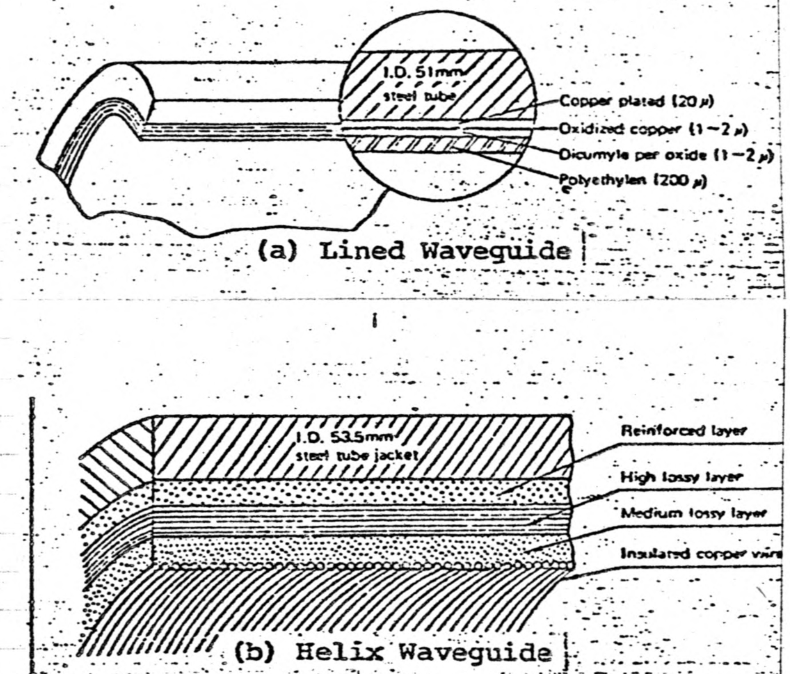


Fig.44. Construction of the Waveguide (Japan)

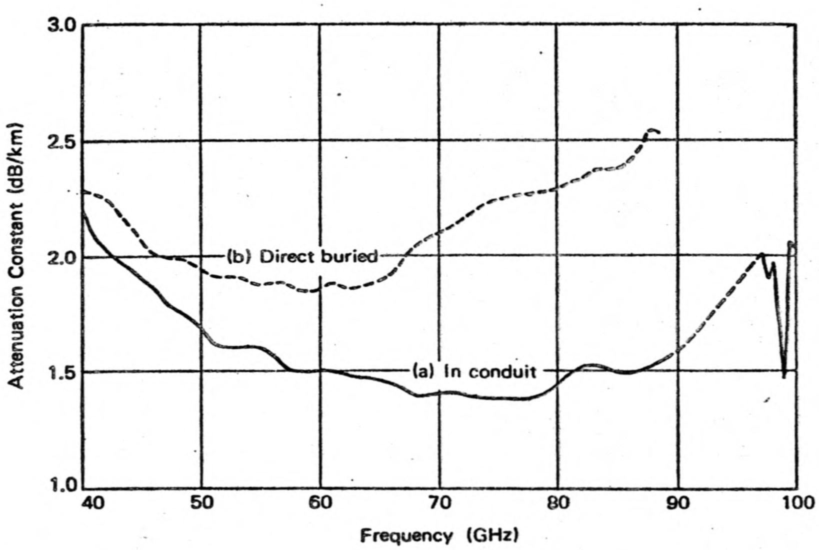


Fig.45–Attenuation characteristics of waveguide lines installed in a straight line.

C. Waveguide Installation in Cable Tunnel

N.T.T. installed 3.8km waveguide in the cable tunnels in Tokyo in 1975 for field evaluation tests. The test route had many sharp bends and the following special waveguides were used.

34 pcs. of 14mm flexible waveguide

41 pcs. of miter corner waveguide

44 pcs. of taper waveguides (for flexible waveguide)

15 pcs. of TE_{02}, TE_{03}, mode filter

The transmission loss was as follows

around 50 GHz 32dB/3.8km

80 GHz 25dB/3.8km

4. Waveguide System in France

A. History and Future Program

1963; Research was started

1971; Saint-Amand--Meudon test link of 10km was constructed. (Type A waveguide was used.)

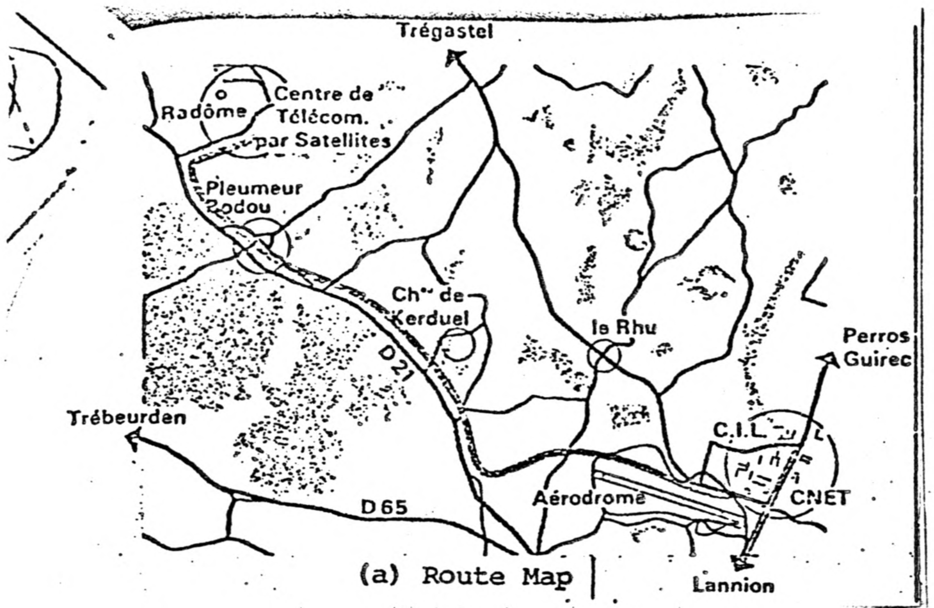
1973; Lannion--Pleumeur-Bodon test link of 15km long was constructed. (Type B waveguide was used.)

1974 to 1976; New type of waveguide is under study.

1977 to 1979; New test line is expected to be installed in 20km length with starting 5km in 1977 using new type of waveguide.

B. Experimental Line (Lannion--Pleumeur-Bodon, 1973)

1) Route



total length; 15km

Figure 46. Experimental Line Route

2) Performance

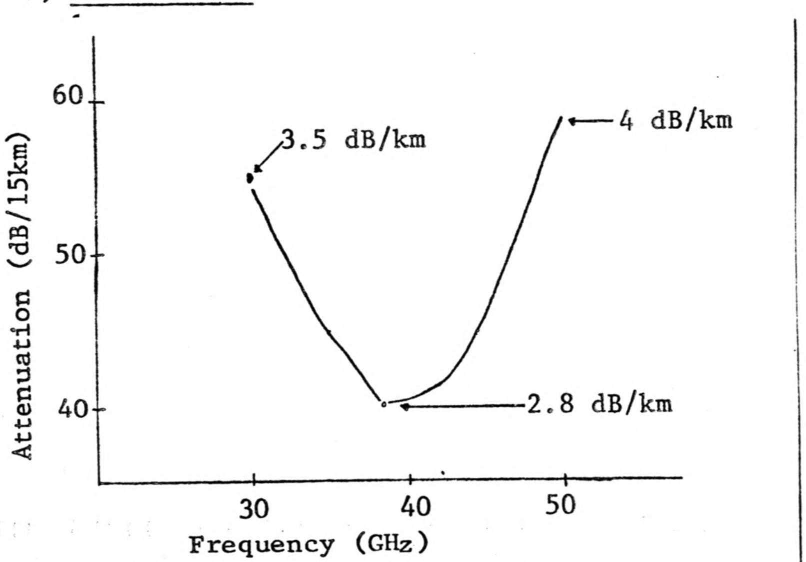


Figure 47. Experimental Line Performance

C. Waveguide Developed in France

1) Type A

50mm diameter helix waveguide with steel jacket.

- The configuration is similar to B.T.L. helix waveguide and Japanese helix waveguide.

- In 1971, 10km of this type of waveguide was installed between Saint-Amand--Meudon (near Paris).

- The performance was 4 ~ 6dB/km after installation.

2) Type B

50mm diameter epoxi resin helix waveguide

- The configuration is similar to British lightweight helix waveguide.

- This type of waveguide was fabricated by continuous production machines, and 15km of waveguide was installed directly underground without mechanical protection between Lannion and Pleumeur-Bodon.

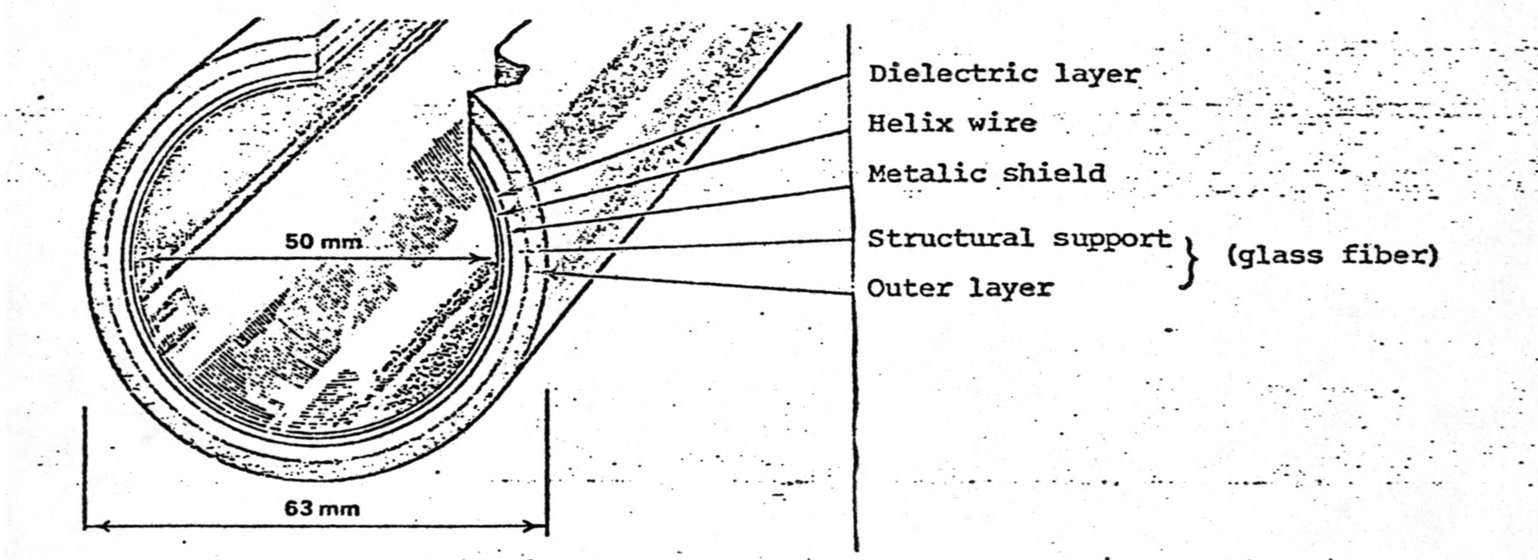


Fig. 48. Construction of the Waveguide (France)

3) Type C

- Configuration

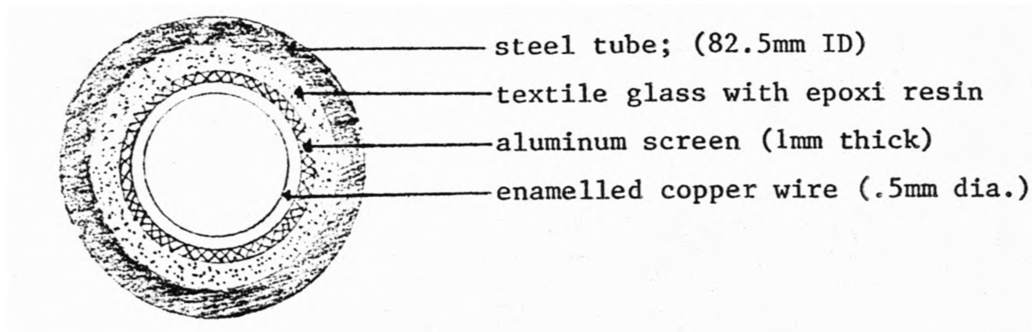


Figure 49. Configuration

- Development Status

  Several different 600 meter lengths of waveguide have been laid and fundamental study on performance is ongoing.

- Performance

  Typical performance is as follows.

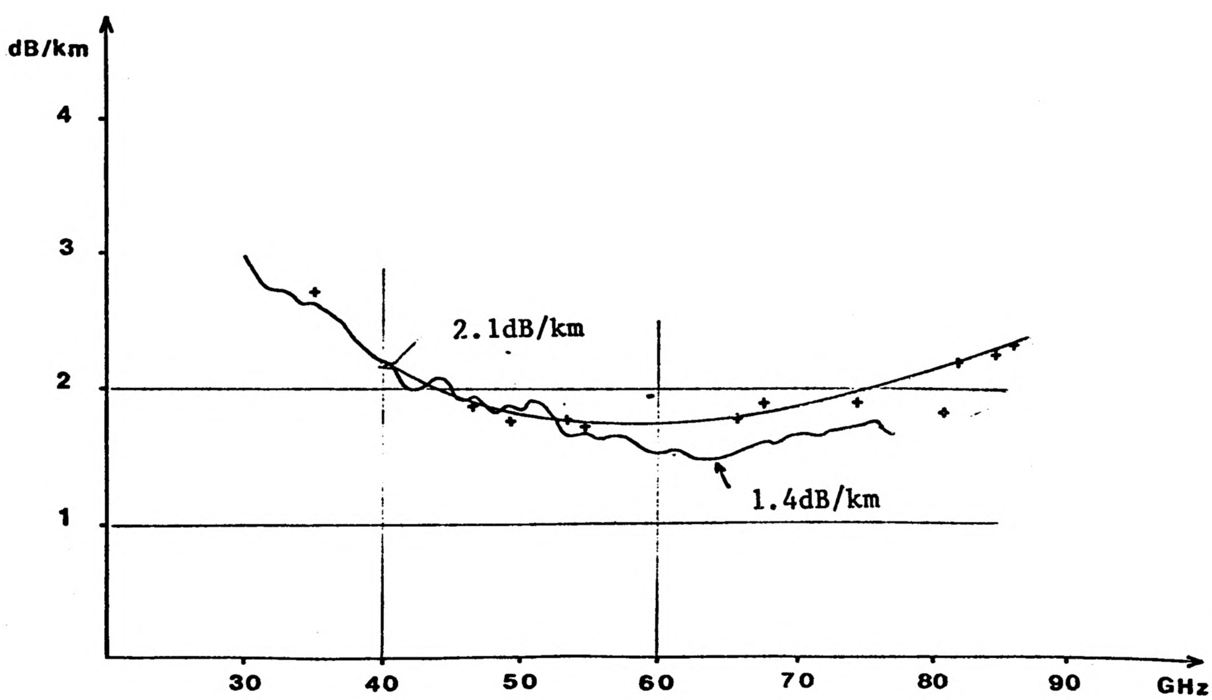


Figure50 Klystron measurements of 600-meter waveguide before and after burying

4) <u>Type D</u>

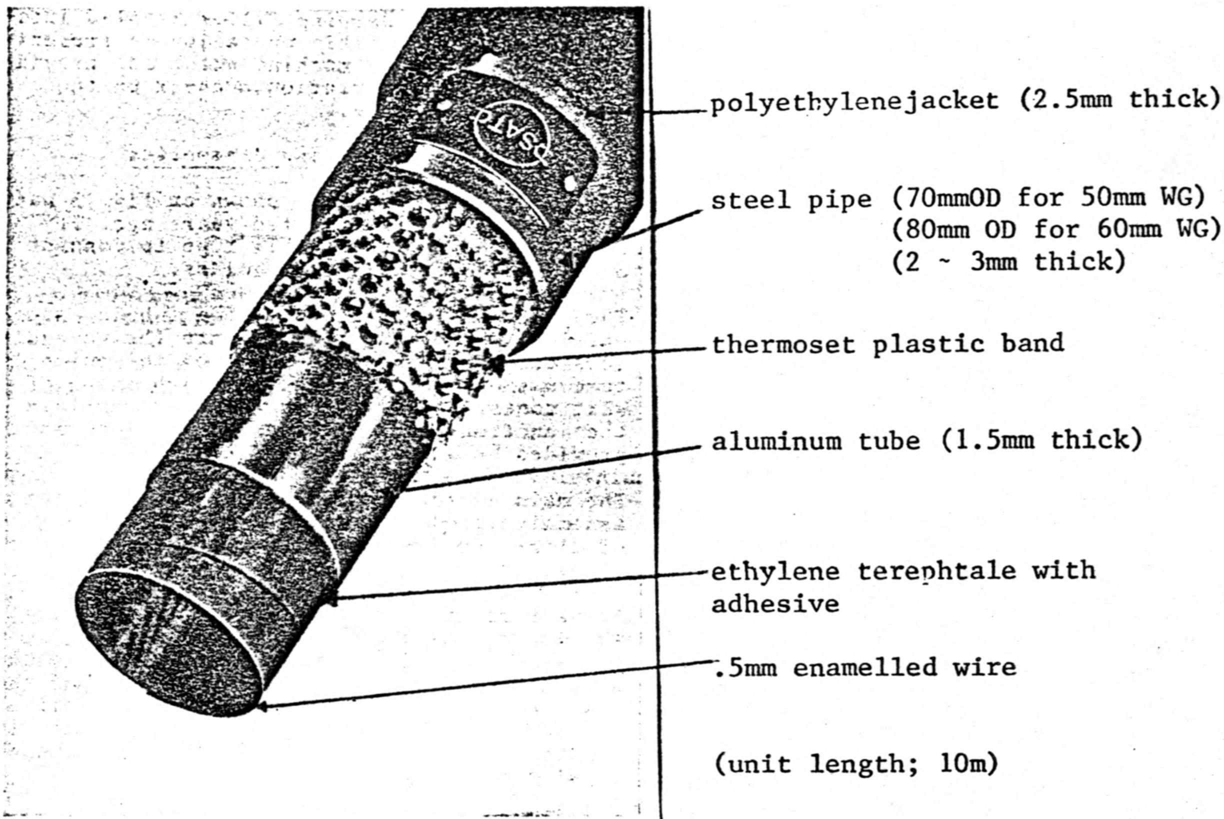


Fig.51. 50 mm HELICAL WAVEGUIDE

- Development Status

  Under study of fundamental performance and installation technique

- Performance Achieved

  Loss of less than 2dB/km in 45 ~ 60 GHz except loss peaks around 51 and 53 GHz in a straight line.

  Loss increase in a bend is .2 ~ .3dB/km at 72 GHz.

- Future Aspect

  In France, they are expecting this type of waveguide will be mainly used, and they have plans to change the diameter to 60mm to reduce the loss.

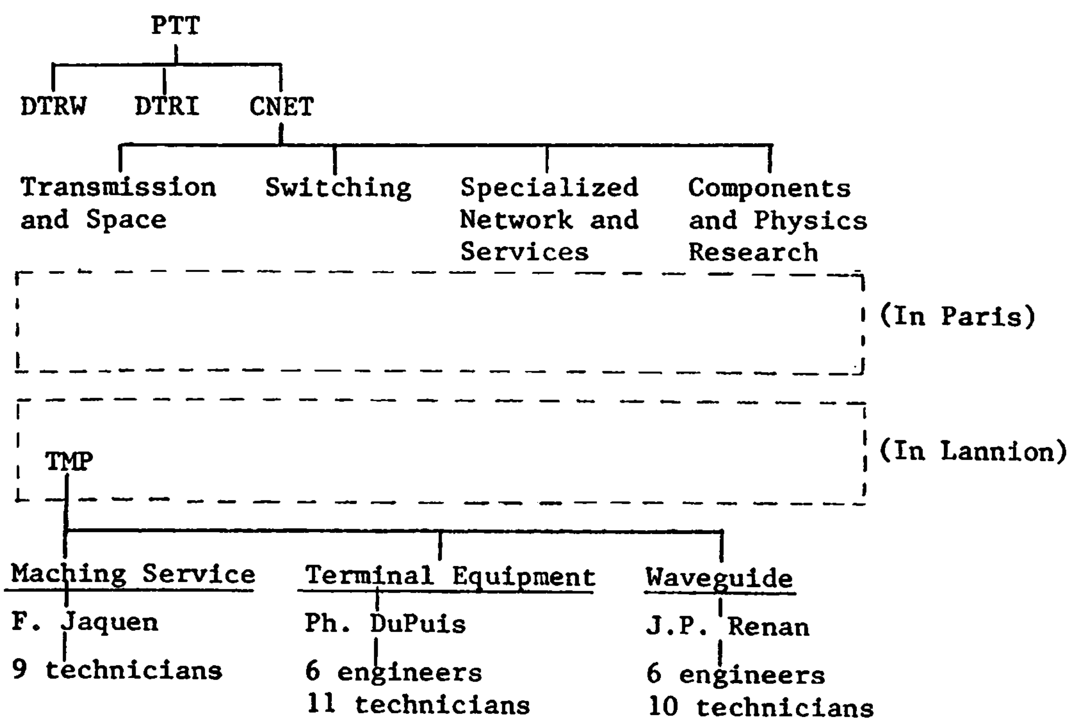
D. Others

1) Features of French Waveguide System

Continuous production plant of waveguide was achieved. It sets the unit length more than 10m.

Direct burial installation of waveguide has been adopted and is being used to make installation easier.

2) Organization for Research and Development of Waveguide System



Note - CNET = Centre National d'Etudes des Telecommunications
French National Telecommunications Research Center

TMP = Transmission, Modulation and Accoustic Division

Figure 52. Organization for Research & Development of Waveguide System

Companies associated with CNET in Waveguide Project

Cable De Lyon	:Waveguide
Societe Anoyme de Telecommunications	:Waveguide, IF equalizer modem
CIT	:Diplexer, signal distributor, modem
LTT	:Branching filter, IF device
Thomson C.S.F.	:Local oscillator, equalization
TRT (Phylips)	

5. Research and Development in West Germany

A. History and Future Program (The German Post Office, FTZ)

1957; A first 300m experimental line.

1964
to ; Three experimental lines each 3km long using different
1971 waveguide.

1978; Completely stop research and development.

B. Route

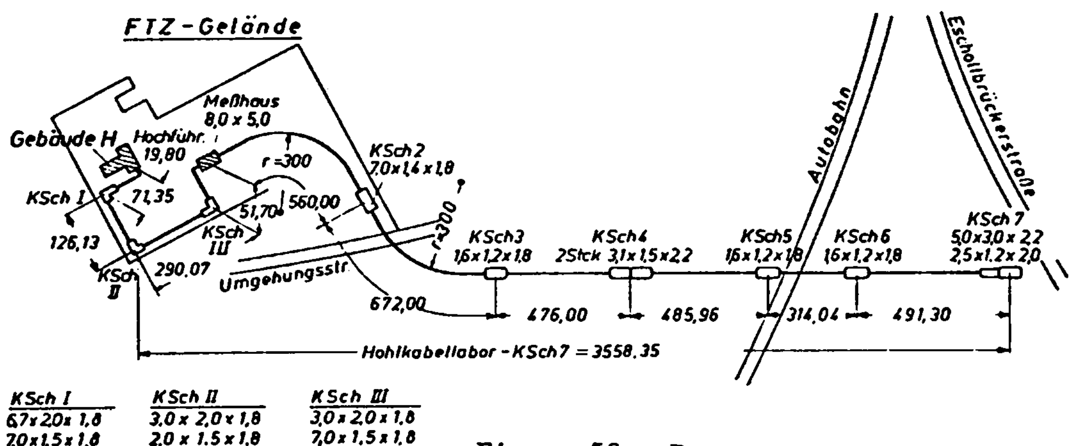


Figure 53. Route

C. Waveguide Developed in West Germany (inner diameter 70mm)

1) Type I

Dielectric Lined Waveguide consists of AlMgSi tube with 90μm thick lossy dielectric lining. (Er=3.1 tanδ=.06)

0.5m long crossed foil filters at intervals of 30.5m

2.5dB/km in 30 ~ 50 GHz

2) Type II

Dielectric Lined Waveguide consists of AlMgSi tube with 90μm thick lossy lacquer lining.

1.0m long helical filter at intervals of 19m (helix waveguide)

loss was unexpectedly high and partly replaced

3) Type III

Helix Waveguide with steel tube jacket.

.75dB/km ~ 2.0dB/km in 40 ~ 80 GHz, 1.0dB/km at 50 GHz

Performance in straight was best out of Types I and III. High cost and loss increase in curved sections required improvements.

4) Type IV

Dielectric Lined Waveguide consists of copper plated steel tube with 180μm polyethylene lining under evaluation.

5) Type V

Improved Type I waveguide with 200μm thick polyethylene lining

1.0 ~ 1.7dB/km in 30 ~ 50 GHz, 1.2dB/km at 50 GHz

6) Type VI

Improved Type II waveguide with aluminum oxide lining 0.75 ~ 1.5dB/km in 30 ~ 60 GHz, .75dB/km at 50 GHz.

D. Installation

Waveguides are pushed into PVC ducts of 126mm ID from the manholes spaced at intervals of 310m ~ 670m. Waveguides are equipped sleeves carrying six polyamid rollers at intervals of 1.5m.

E. Other Studies

1) 90^o Corner Waveguide

90^o corner waveguide with 140mm diameter has been studied. The insertion loss was improved by increasing the diameter, but TE_{02} mode conversion level did not come down as it was expected. It requires two 2.7m long 70-140mm tapers and it is not practical in actual use. (Refer to "Millimetric Waveguide Systems" p.68.)

2) Band Diplexing in Overmode Rectangular Waveguide

The branching network composed of overmode rectangular waveguide has been studied. It enables the considerable reduction in size and weight. Problems associated with TE_{01} mode circular waveguide such as TE_{02} mode generation are less than conventional design. (Refer to "Millimetric Waveguide Systems" p.147.)

F. Other Information from Discussion at Braushweig University

1) It would be possible to decrease the insertion loss of beam splitter couplers by using laminated dielectric

materials. (Reference: AAM Saleh, "Polarization-Independent Multilayer Dielectrics at Oblique Incidence", BSTJ, 1975, p. 1027.)

2) They use "Plexiglas" (German) as material for electroforming mandrel. ("Plexiglas" = polymethyl methacrylate)

3) The source from which they get dielectric materials is: Emerson and Cuming Inc., Canton, Mass 02021.

Sales office: Box 1209
405 North Bowsen
Richardson, Texas

Catalogs:
1. Dielectric Materials
2. Microwave Products (include absorber foils)