A Waveguide Quadruplexer System*

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Summary—Practical design considerations are presented for a relatively simple four-channel waveguide branching system. The most important electrical characteristic of this system is an extremely low pass-band reflection coefficient (better than 1.5 per cent in 30-Mc band) which has only very small variations with the environmental conditions.

Introduction

In a wide-band frequency-modulated microwave communication system, the ultimate signal-to-noise ratio is usually seriously affected by the feeder distortion of the microwave transmission network [1].

The feeder distortion is the result of the time delayed reflections which are generated by the discontinuities of the long, radio-frequency line. These can be divided into end (antenna, branching system) and internal (joint) discontinuities. In this paper, one source of the end reflection, a branching system with extremely low-reflection coefficient, will be described. A newly developed low-reflection antenna [2] and waveguide system [3] for the same microwave equipment were discussed by the authors elsewhere.

The basic requirements for a modern branching system are the following:

1) low pass-band reflection coefficient,
2) high stop-band insertion loss,
3) high isolation between receiver and transmitter channels,
4) simplicity and reproducibility of fabrication,
5) small size and weight,
6) easy tuning,
7) insensitivity to the environmental conditions.

Apparently, some of the above requirements contradict each other. For instance, in the 2000-Mc band, low loss and simplicity of manufacturing implies the use of waveguide components. However, these components are relatively large and heavy. Of the known types of waveguide filter design, the direct-coupled cavity type assures the smallest over-all size [4]. At the same time, the tuning of this type of filter is relatively difficult. The independency of the filter characteristics from the transmitter output and receiver input impedance can be achieved by the insertion of ferrite isolator elements. These components, however, are temperature sensitive. With an increasing number of RF channels, the branching system becomes more and more complicated, while the pass-band reflection coefficients increase. This limits the bandwidth of the individual RF channels and reduces the over-all voice channel capacity.

The branching system to be discussed is a four-channel waveguide branching network (quadruplexer). As will be shown, this system results in a reasonable compromise between the various requirements. It also can be used as the terminal unit in a more complicated branching system, which utilizes more than four RF channels.

Principle of Operation

The basic concept of the quadruplexer arrangement is shown in Fig. 1. According to the indicated scheme, the quadruplexer is a network with five terminating reference planes. These terminating reference planes will be referred to as terminals in the following. The main, or antenna, terminal A supports all the RF channels of which two are usually transmitter channels, 1 and 2, and two are receiver channels, 3 and 4.

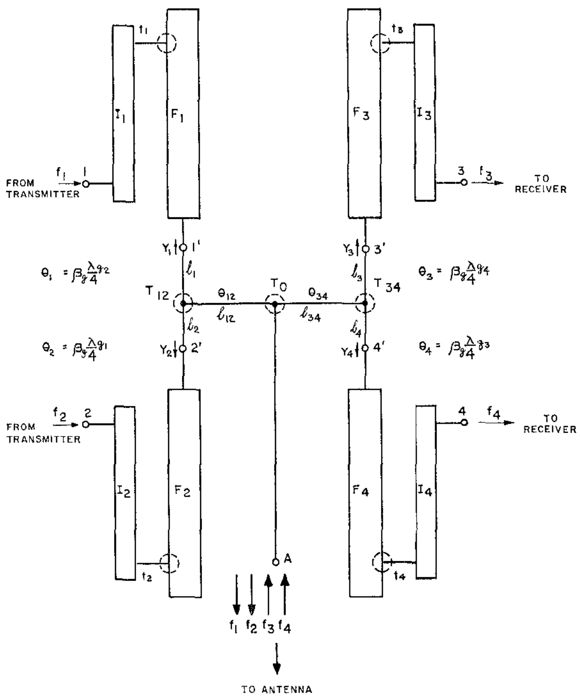

Fig. 1—Basic concept of quadruplexer arrangement.

F_1, F_2, F_3, F_4 = filter sections
I_1, I_2, I_3, I_4 = isolators
t_1, t_2, t_3, t_4 = coaxial $-wg$ transitions
T_{12}, T_{34}, T_0 = Tee junctions.

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Ideally, the network connects terminals 1, 2, 3 and 4 to A without any loss in a narrow frequency band centered around f_1, f_2, f_3 and f_4, respectively, while there is no connection between the terminals at any other frequencies. Terminal A is physically connected to terminals 1, 2, 3 and 4 by means of six transmission-line sections. At f_1, f_2, f_3 and f_4 frequencies, the normalized input impedance at terminal A can be unity if the six-line sections are chosen properly and the terminating impedances of these lines have certain frequency functions; namely, they are properly-designed filter impedances. The input impedance of a wave filter depends on its terminating impedance and its internal structure. In a microwave communication system, these terminating impedances are the receiver (crystal mixer) input impedance and the transmitter (traveling-wave tube) hot output impedance. All these vary with the working and aging conditions and may change if crystals or tubes are replaced. Furthermore, different lengths of cable are usually used between the equipment and the branching system which may cause unpredictable phase changes in the receiver and transmitter reflection coefficients. Therefore, it is mandatory to use some kind of isolating attenuator. In Fig. 1 these attenuators are represented as ferrite isolators.

Factors Affecting the Pass-Band Input Reflection Coefficients

The input reflection coefficients at terminals 1, 2, 3 and 4 require less consideration. Even if the band-pass filters are only approximately tuned and terminal A is approximately matched, the generated reflections are absorbed by the ferrite isolators. Therefore, this reflection coefficient is practically determined by the ferrite components itself. Furthermore, the requirement for a low-reflection coefficient at these terminals is less severe because the length of cable between the branching system and equipment is short and the corresponding feeder distortion is low.

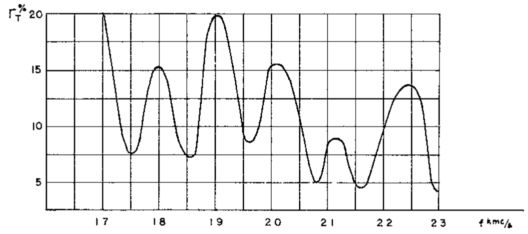
The reflection coefficient at terminal A is far more important. This is affected in a pass band by the following factors:

1) the reflection coefficient of the loads at the equipment end,
2) the input or output reflection coefficient of the ferrite isolators,
3) the reflection coefficient of the coaxial to waveguide transition,
4) the input impedance of the terminated band-pass filter,
5) the characteristics of the coupling line network,
6) the proximity effect caused by other filters,
7) the junction effects of the Tee connectors.

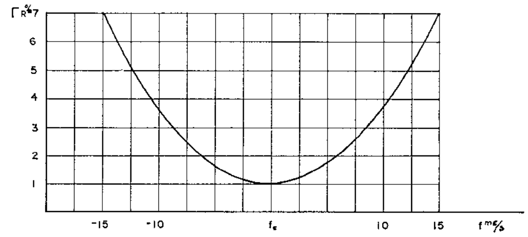
Only the most important factors will be briefly discussed here.

Terminals 1, 2 and 3, 4 are connected to the transmitters and receivers of the communication equipment at one repeater station, while at the next repeater station 1, 2 and 3, 4 are interchanged with each other.

Fig. 2(a) and 2(b) show the typical transmitter and receiver output and input reflection coefficients, respectively. These reflection coefficients are lowered by the ferrite isolators (by at least 26 db) to a 0.42 per cent average, effective terminating reflection coefficient.



(a)



(b)

Fig. 2—(a) Typical value of the output reflection coefficient of the 7642 TW tube. $\Gamma_{T\,av} = 10.3$ per cent (contribution to the average top-channel distortion is determined by $\Gamma_{T\,av}$). (b) Average value of the receiver input reflection coefficient around the f_c carrier. $\Gamma_{R\,max} = 7$ per cent (contribution to the average top channel distortion is determined by $\Gamma_{R\,max}$).

A five-section direct-coupled filter is used as the filter building block of the quadruplexer system. The stop-band insertion-loss requirement could be fulfilled by a four-section filter. However, the five-section arrangement results in more symmetrical group-delay variations and greater flexibility in tuning.

In the accepted design six pair of inductive posts are placed approximately at equal distances along the waveguide. In the middle of the waveguide, between each pair of inductive posts, additional (coupling) screws are added which make it possible to vary the reflections generated in these cross sections. The effective line length between the reference planes of the inductive posts is made variable by other (tuning) screws placed equidistantly between the coupling screws.

Fig. 3 shows the measured input impedance curve of such a filter. The reference plane is fixed at the cross section where the effective short circuit can be measured in the input impedance at a frequency considerable higher than the center frequency of the pass band. Fig. 3(a) shows the impedance curve in the transition and stop band, while Fig. 3(b) shows the curve in the pass band.

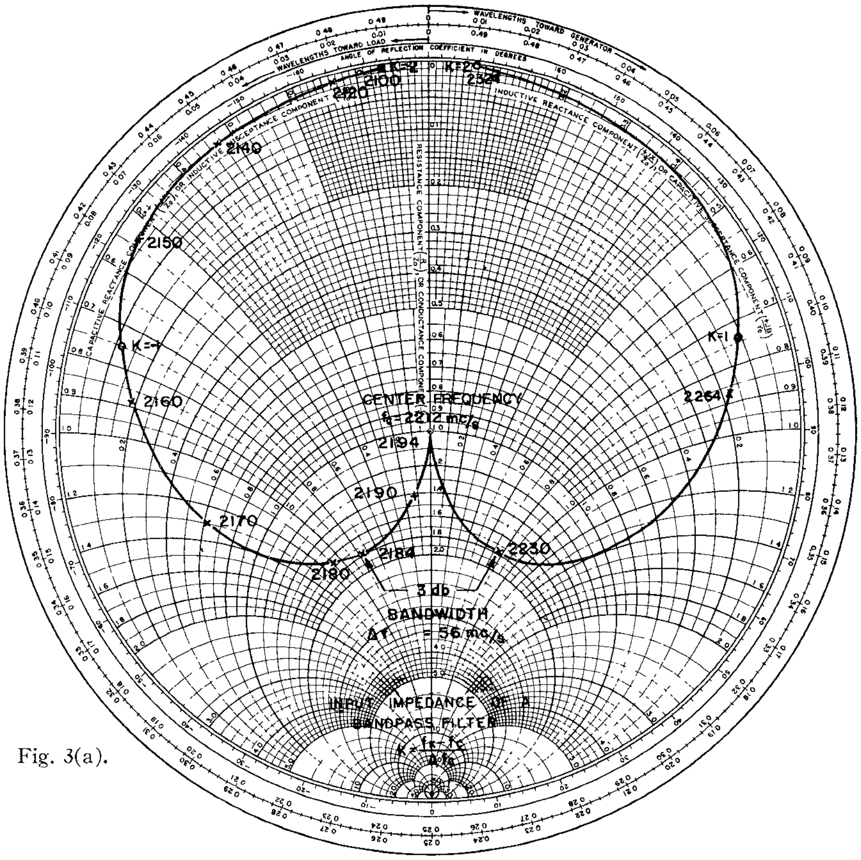

K=-2
K=2
2120
2100
2140
2150
K=-1
K=1
2160
2264
CENTER FREQUENCY
f0=2212 mc/s
2194
2190
2170
2184
2180
2230
3 db
BANDWIDTH
Δf = 56 mc/s
INPUT IMPEDANCE OF A
BANDPASS FILTER

Fig. 3(a).

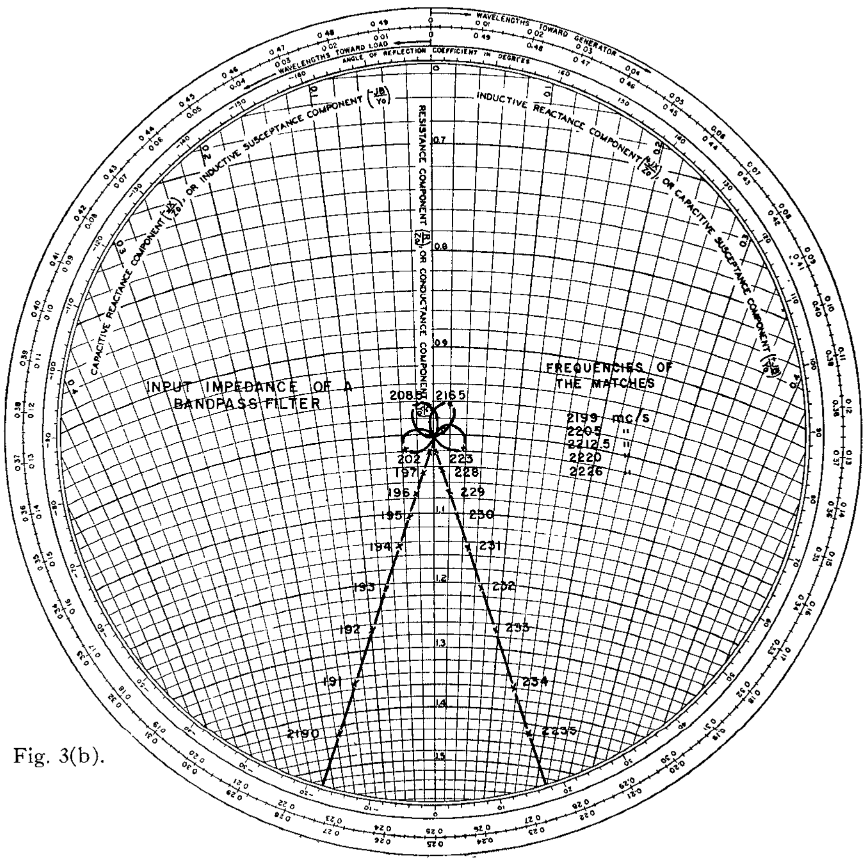

INPUT IMPEDANCE OF A
BANDPASS FILTER
FREQUENCIES OF THE MATCHES
2199 mc/s
2205 "
2212.5 "
2220 "
2226 "
2085
2165
202
223
197
228
196
229
195
230
194
231
193
232
192
233
191
234
2190
2235

Fig. 3(b).

Fig. 4 indicates the reflection coefficient in the pass band, which is less than 1.5 per cent in ±15-Mc band, if the filter is properly terminated.

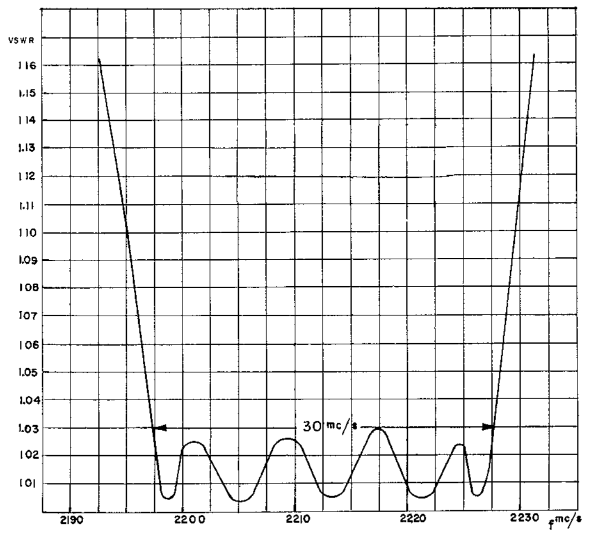


Fig. 4—Pass band reflection coefficient of a band-pass filter.

Fig. 1 shows the electrical schematics of the coupling line network. In this figure, terminal A represents a reference plane in the antenna line very close to the T_0 junction, while 1′, 2′ 3′, and 4′ represent the reference planes where the band-pass filters show their stop-band short circuit.

The line section between T_{12} and 1 is terminated with filter F_1 which has its pass band at a frequency f_1, or a wavelength λ_{g1}. Similarly, terminals 2, 3 and 4 pass the waves with λ_{g2}, λ_{g3} and λ_{g4} wavelength. According to Fig. 1, the line section between T_{12} and 2 has no effect on the junction T_{12} at a wavelength λ_{g1}, assuming that this branch line is terminated by a perfect short circuit. However, the line sections between 3 and T_{34} are not resonant at λ_{g1} wavelength (their lengths are $\lambda_{g3}/4$ and $\lambda_{g4}/4$, respectively). Consequently, a finite reactance will appear at T_{34}. The right-hand side of the network will cause the smallest effect at both λ_{g1} and λ_{g2} wavelength if the l_{34} line length is determined at $\lambda_{g12} = (\lambda_{g1}\lambda_{g2})^{1/2}$ to compensate the reactance, which would appear in T_{34} at this wavelength. The above consideration can be applied for the left-hand side of the network at $\lambda_{g34} = (\lambda_{g3}\lambda_{g4})^{1/2}$ to determine l_{12}. Assuming ideal filters with unit input impedance in their pass bands and zero input impedance in their stop bands, Table I contains the calculated input admittance values at terminal A for a typical frequency plan. The calculation neglects the junction effects.

According to Table I, the deviations from the unit admittance are small. These deviations shift the filter input admittance curve slightly. However, this effect can be easily compensated by the tuning of the band-pass filter.

In practice the values in Table I are modified by the fact that the filters are not ideal. According to Fig. 3(a), the input impedance of the band-pass filter drops rapidly from unity as K increases (K is the relative detuning of the filter expressed in 3-db bandwidth units). If $|K| \geq 2$, the filter already can be approximated by a short circuit. These conditions can be analyzed in any pass band, say in channel 4. Here, the effect of filters F_1 and F_2 are negligible, because for these filters $|K| \gg 1$. Channel 3 filter, however, is tuned in the transition band of F_4 and the two filters mutually affect each other. For instance, for $K=1$ and 2, the input impedance of F_3 will be $0.11+j0.75$ and $0.05+j0.06$, respectively. The reactive component can always be compensated by a correction of the l_3 line length, but the real component appears parallel with the F_4 filter and causes loss and mismatch.

TABLE I
CALCULATED LINE LENGTH EFFECT FOR A TYPICAL FREQUENCY PLAN

Channel	Carrier Frequency (Mc)	Normalized Input Admittance at Terminal A
1	1912.5	$1.0170-j0.0006$
2	1970.5	$0.9788+j0.0006$
3	2212.5	$1.0240-j0.0011$
4	2270 5	$0.9720+j0.0020$

CHARACTERISTICS OF THE COMPLETE BRANCHING SYSTEM

Construction

In the case of a high-quality branching network, the maintenance of the mechanical dimensions in operations is extremely important. If the desired reflection coefficient is in the order of 1 per cent, then the inside dimensions of the waveguide structure should be kept within a few thousands of an inch after the system is tuned, in order to assure a reflection coefficient variation of not more than 0.1 per cent.

The above requirement is achieved by the use of a rigid supporting frame and a nonstandard, heavy-wall waveguide.

Figs. 5 and 6 show the mechanical construction and the outside dimensions of the quadruplexer.

The microwave structure is built up from copper waveguide (4.300″×2.150″ inside dimensions, with 0.125″ wall thickness). Relatively large manufacturing variations

$$\left(\begin{array}{c} +\ 0.000'' \\ -\ 0.008'' \end{array} \right)$$

are tolerated in the cross section because the tuning method of the filters automatically eliminates the effects of manufacturing variations. However, the cross-section dimensions of the waveguide at terminal A are sized to

$$4.300'' \begin{array}{c} +\ 0.000'' \\ -\ 0.002'' \end{array} \times 2.150'' \begin{array}{c} +\ 0.000'' \\ -\ 0.002'' \end{array}$$

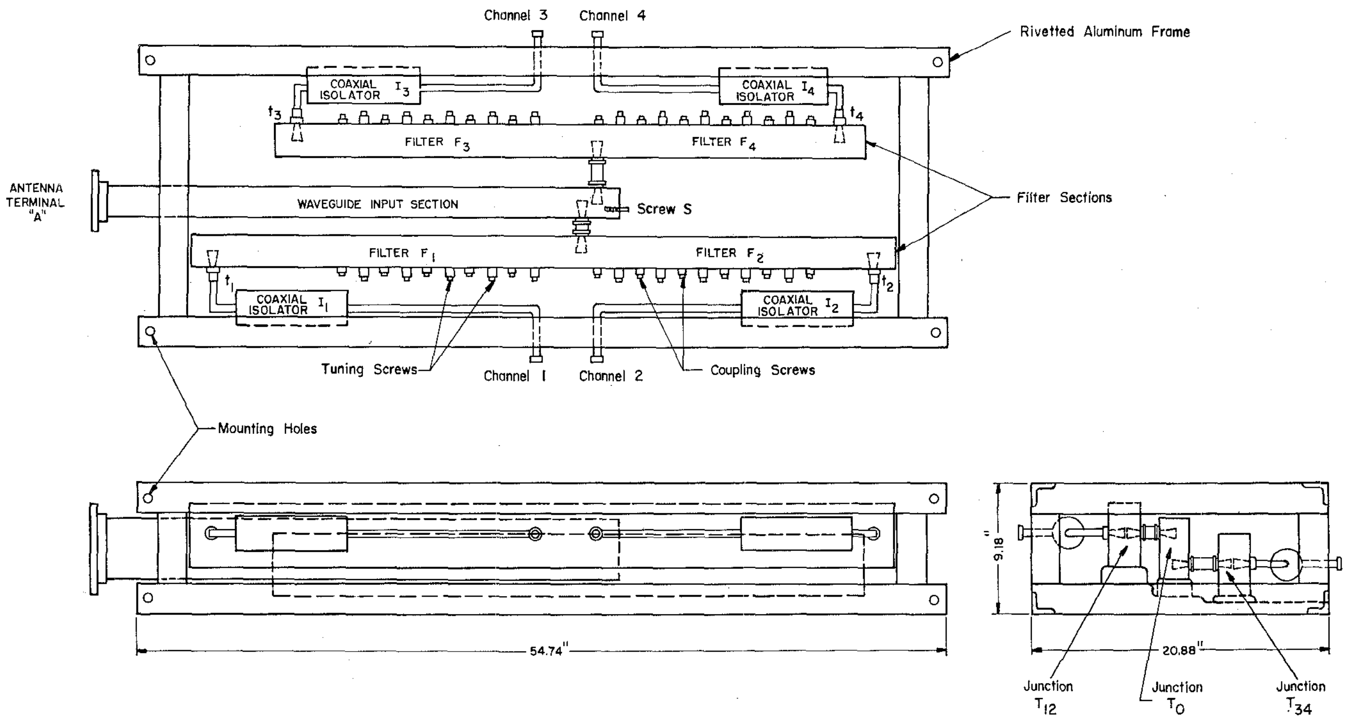


Fig. 5—Mechanical layout of the quadruplexer.

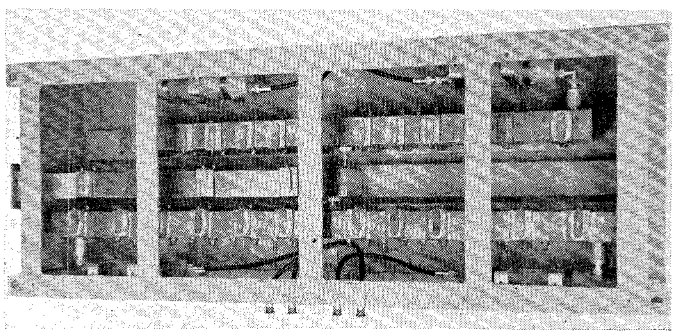


Fig. 6—Internal view of quadruplexer.

to assure a low-reflection transition between the quadruplexer and the waveguide feeder [3]. The efficiency of the joints between the various microwave components (at T_{12}, T_{34} and T_0) were the object of careful consideration. Silver-plated and rhodium-flashed metex washers are used in the flat flange joints at the ends of the coaxial coupling lines.

Tuning

As was mentioned previously, the aim of the discussed quadruplexer design was to obtain and maintain pass band reflection coefficients at terminal A in the order of a few per cent. Obviously, this specification imposes rather severe requirements on the necessary test equipments. Primarily, for tuning purposes, an intermediate power sweep generator and a high-quality waveguide directional coupler were developed. This coupler has tight coupling (approximately 7 db) to allow the detection of small reflected signals. The directivity is approximately 52 db, which is equivalent to 0.25 per cent internal coupler reflection, and thus ± 0.25 per cent error in the measurement of reflection coefficient.

The tuning procedure is reasonably straightforward. The resonant frequencies of the consecutive filter cavities follow a certain order to assure the low-reflection coefficient. The tuning procedure is based on monitoring the reflection coefficient at terminal A with an oscilloscope.

Due to the proximity effect, some interaction can be experienced between the individual filters. Therefore, it is necessary to make a second approximation in the tuning, a slight readjustment of the first cavities of the individual filters.

The tuning time of a quadruplexer is basically affected by two factors: 1) the skill of the individual operator, and 2) the reproducibility of the contact at the coupling and tuning screws.

Considerable time was spent to obtain a satisfactory design for the screw mechanism. The design requirements for such a mechanism can be summarized as follows:

1) smallness and reproducibility of the contact impedance between the screw and the waveguide wall during tuning,

2) locking facilities, which do not change the screw position after the filter tuning is completed,

3) simplicity, for quantity production.

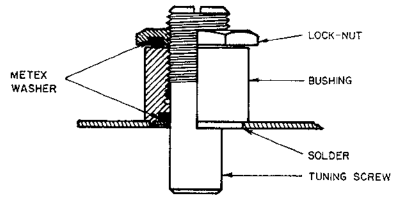


Fig. 7—Tuning mechanism.

TABLE II

ELECTRICAL AND MECHANICAL CHARACTERISTICS OF THE QUADRUPLEXER

Characteristics	Production Figure*	
	At Room Temperature	In −80 to +150 F Temperature Range
Size	54.74×20.88×9.18 inch	
Weight	200 pounds	
Tuning Range:		
Channel 1	1790–1910 Mc	
Channel 2	1890–2110 Mc	
Channel 3	2090–2210 Mc	
Channel 4	2190–2310 Mc	
Bandwidth between the 3-db insertion loss points	55–60 Mc	
Pass-band loss (at carrier frequency) including isolator loss	1.27 db	
Stop-band loss (at ±80 Mc from carrier frequency	70 db	
Minimum isolation between receiver and transmitter channels	75 db	
Average reflection coefficient in the 30-Mc pass band at terminal A†	1.3 per cent	2.1 per cent
Maximum input reflection coefficient in the 30-Mc pass band at terminal A†	1.7 per cent	2.7 per cent
Average input reflection coefficient in the 30-Mc pass band at terminal 1, 2, 3, or 4	3.8 per cent	
Maximum input reflection coefficient in the 30-Mc band at terminal 1, 2, 3 or 4.	4.5 per cent	

* Average figures based on 12 production units. † The load on terminals 1, 2, 3, 4 is as given in Fig. 2.

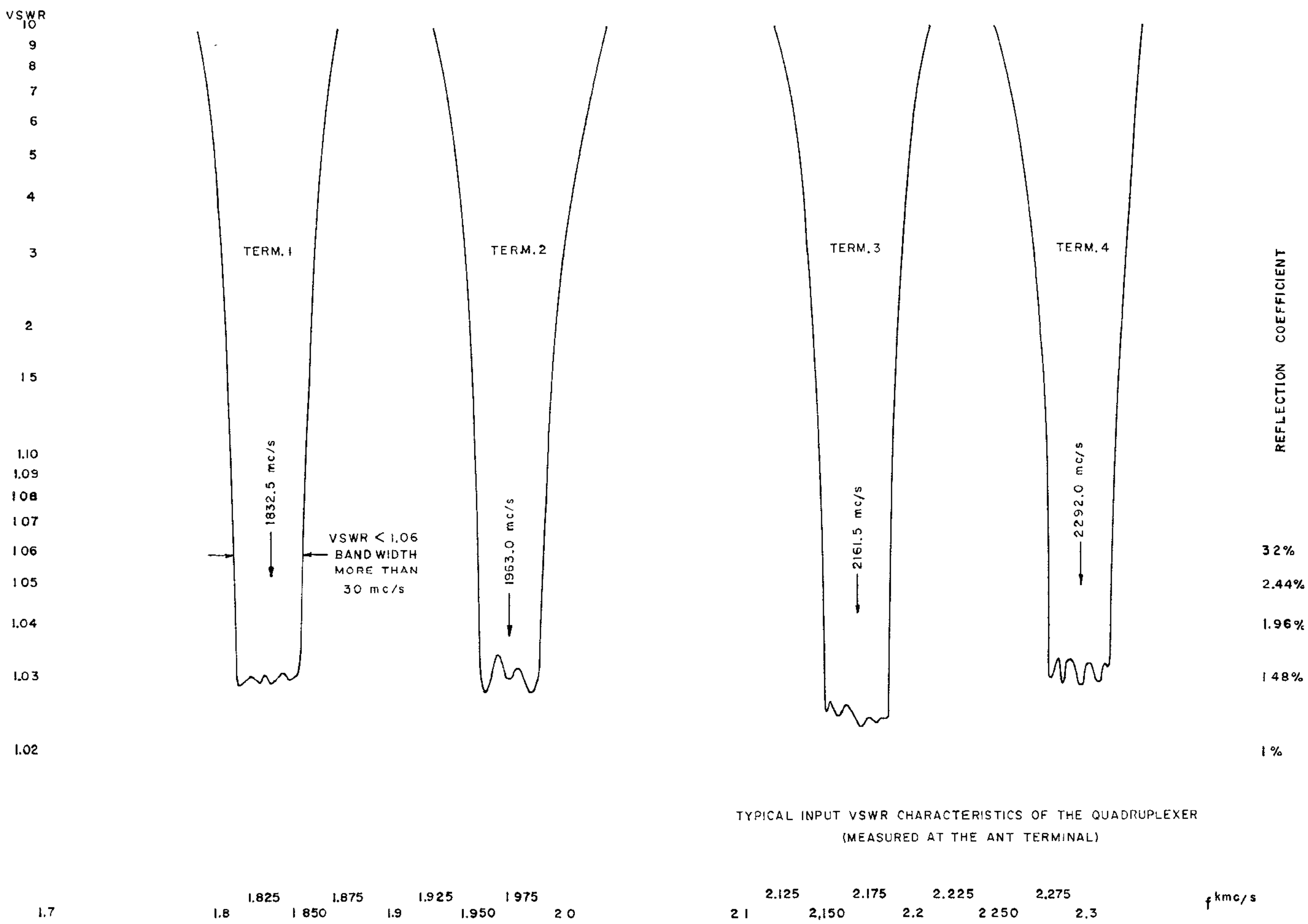


Fig. 8(a).

Three different types of screw arrangements were designed and tested. Fig. 7 shows the finally accepted version. This arrangement consists of a tuning or coupling screw with a threaded portion and a plain surface which makes contact on a metex washer firmly held in the bushing. This method provides contact between the screw and the bushing in the plain of the waveguide wall. Very exact control can be exerted over each cavity whether the locking nut is loose or tight. The lock nut also has a metex washer imbedded in its lower surface to provide locking tension. The lock nut does cause some drag on the screw when it is tightened, but this can easily be overcome by holding the screw against the thread. This method is adapted for use in the quadruplexer because the larger cost in fabrication is compensated by the saving in the tuning time.

With the above precautions, the average tuning and testing time of the completed four-channel branching system is approximately eighteen working hours.

Electrical Characteristics

The major characteristics of the quadruplexer are exhibited in Table II. The indicated figures are averages based on twelve production units. Fig. 8 (pp. 302–303) shows in more detail some of the electrical characteristics. Fig. 8(a) shows a typical input reflection coefficient characteristic at terminal A. As can be seen, each channel has approximately 1.5 per cent average reflection coefficient in a 30-Mc band while there is some variation in the shape of the pass band. Fig. 8(b) indicates the insertion-loss characteristics between terminal A and a typical output terminal. The larger part of the midband insertion loss is caused by the ferrite isolator. Fig. 8(c) represents the isolation between an adjacent transmitter and receiver channel (channels 2 and 3). It should be noted that the quadruplexer arrangement increases the transmitter-receiver isolation relative to the filter insertion loss because of the additional filter characteristics of the T_0 junction.

Effect of the Environment

General Requirement

In a long-haul microwave communication system, the radio equipment usually is installed in a more or less temperature controlled room. However, any decrease in the allowed temperature variations increases the difficulty of maintaining the performance, and a power failure of the heating equipment may cause serious deterioration in the operation. Therefore, it is advantageous to increase the useful temperature range of the individual components. A temperature range of −80°F to +150°F was specified for the quadruplexer.

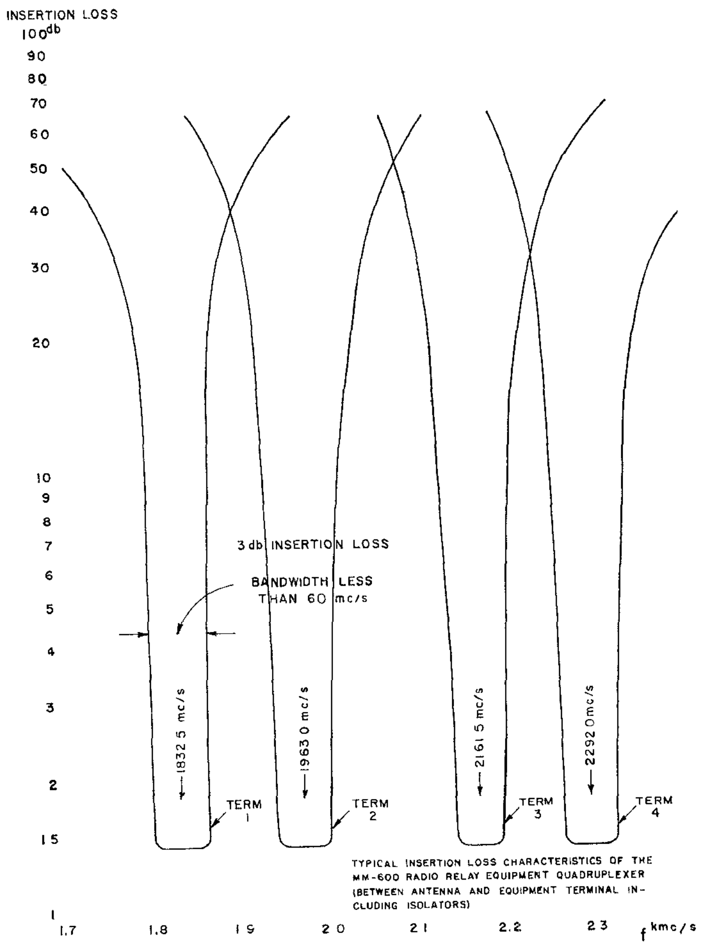


Fig. 8(b)

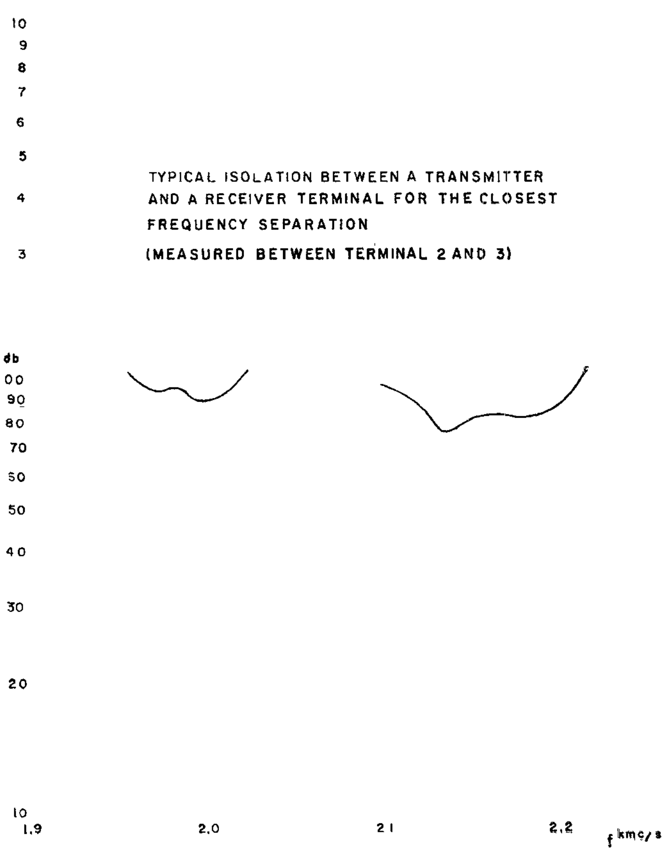


Fig. 8(c)

Among other environmental requirements, the effect of vibration and shock are of particular interest. In spite of the static-type installation of the unit, mechanical vibration may occur in the system during shipping and after installation due to the tower vibration which may be transferred through the waveguide.

Test Facilities and Methods

The temperature sensitivity of the input reflection coefficient of the quadruplexer was measured in a 300-cubic-foot stratosphere chamber. The temperature was measured in the chamber and directly on the waveguide wall of the quadruplexer. The readings were taken when the chamber temperature and the quadruplexer temperature coincided.

The vibration tests were performed on an electrodynamic vibrator with a maximum capacity of 500 pounds. The vibration test basically served to determine the effectiveness of different packing methods. The average of the input reflection coefficient in the 30-Mc pass band served as the basis of comparison. This average value was determined from the measurements performed before and after the vibration test.

Effect of the Temperature

Obviously any temperature change is most pronounced in the input reflection coefficient at terminal A. For this reason only this characteristic was measured. The input reflection coefficient may be affected by three factors:

1) thermal expansion and deformation of the microwave structure,
2) temperature variation of the contact impedance at the tuning screws,
3) temperature variation of the ferrite isolators.

The ferrite isolators were replaced by precision coaxial dummy loads to investigate the first and second factors. Fig. 9 shows the input reflection coefficient at terminal A of a typical channel (channel 3) as a function of temperature. Fig. 9(a), (b), and (c) shows the measured parameter at 75°F, 150°F and 75°F. The last curve was measured after the temperature cycle and shows that the temperature cycle had negligible permanent effect. The average reflection coefficient in the 30-Mc pass band was 0.56, 0.76 and 0.56 per cent at the respective temperatures. It can be concluded that a variation in this order is tolerable and there is no need to build up the structure using a less temperature-sensitive material (invar).

The temperature sensitivity of the individual ferrite isolators were investigated separately and then with the complete unit. Fig. 10 shows the total temperature variations of the reflection coefficient of one quadruplexer channel. This includes the effects of the various factors, but among these the temperature sensitivity of the fer-

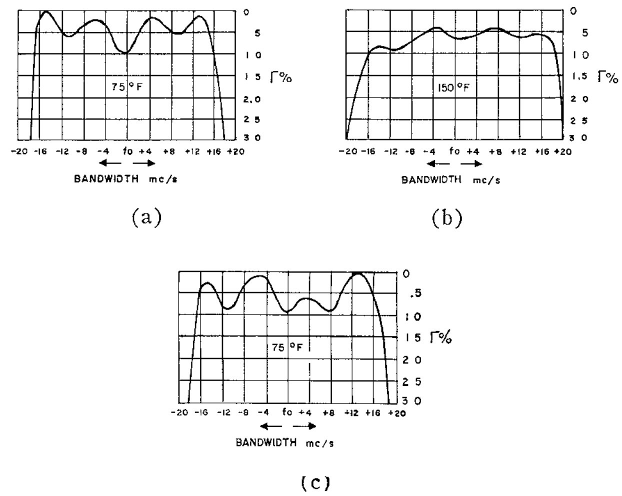


Fig. 9—Input reflection coefficient of a typical channel at terminal A, as a function of temperature (dummy load terminations). $f_0=2172$ Mc. (a) Initial tuning at temperature +75° F, $\Gamma_{AV}=0.56$ per cent. (b) At temperature +150°F, $\Gamma_{AV}=0.76$ per cent. (c) After temperature cycling. $\Gamma_{AV}=0.56$ per cent.

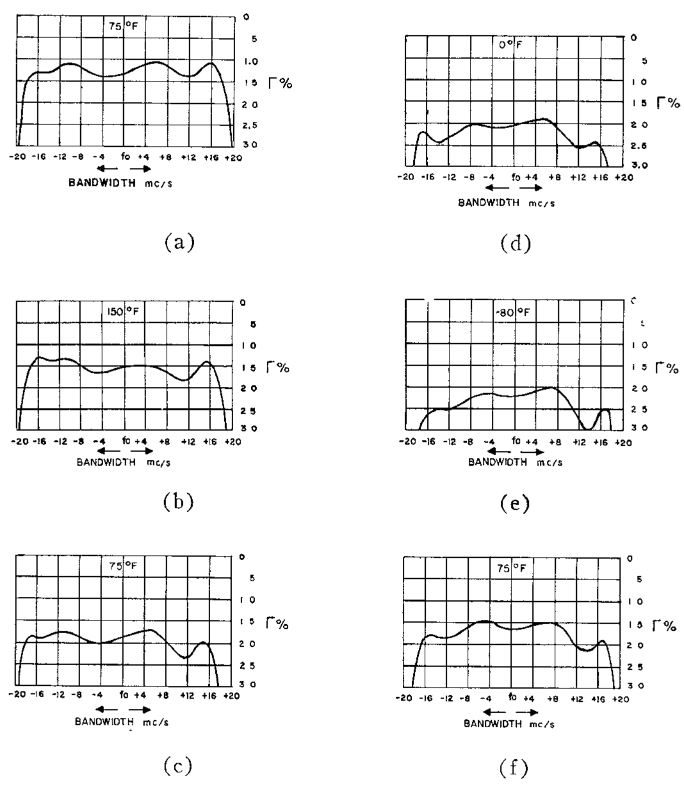


Fig. 10—Input reflection coefficient of a typical channel at terminal A, as a function of temperature (ferrite isolator terminations). $f_0=2172$ Mc. (a) Initial tuning at temperature +75° F. $\Gamma_{AV}=1.32$ per cent. (b) $\Gamma_{AV}=1.50$ per cent. (c) $\Gamma_{AV}=1.97$ per cent. (d) $\Gamma_{AV}=2.26$ per cent. (e) $\Gamma_{AV}=2.35$ per cent. (f) After temperature cycling. $\Gamma_{AV}=1.74$ per cent.

rite isolator is the dominant. In the final design, an external magnet-type isolator is employed with extremely stable electrical characteristics. The series of curves on Fig. 10 shows the temperature variation of the input reflection coefficient for a typical channel through a full temperature cycle (from +75°, +150°, 0°, −80°, +75°F). It can be seen that the variations in the pass band shape are quite tolerable for all practical purposes. Fig. 11 shows the variation of the average reflection coefficient in a 30-Mc pass band as a function of temperature. It can be seen that, in the measured case, the average reflection coefficient is 2 ± 0.7 per cent and shows a certain temperature hysteresis, *i.e.*, has different values at a given temperature depending on the previous temperature conditions of the unit.

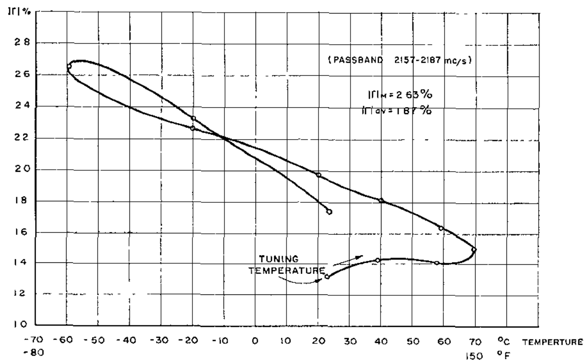


Fig. 11—Typical variation of the average reflection coefficient in one quadruplexer channel.

Vibration

A microwave communication equipment quite often has to be installed in remote areas, and careful handling during shipping cannot always be assumed. Therefore a special, reusable packing case was designed for the quadruplexer, and the effect of vibration was tested.

Fig. 12(a) shows the arrangement of the quadruplexer in the packing case, while Fig. 12(b) indicates the cross section of the packing material. The quadruplexer is lying on a number of damping rods. Each damping rod has a different self-resonant frequency in the 1- through 15-cps frequency band.

The box with the quadruplexer inside was placed and firmly held on the vibration table. The vibration amplitude was adjusted to the curve shown in Fig. 13 and was cycled for two hours. Fig. 14 show a typical filter tuning before and after vibration. Although the figure shows some deterioration in the input reflection coefficient, the change is negligible for all practical purposes. In fact, the comparison between the factory measured data (after tuning) and the field measured data (after installation) did not show any deterioration within the measurement error. These latter measurements were conducted on twelve quadruplexer units.

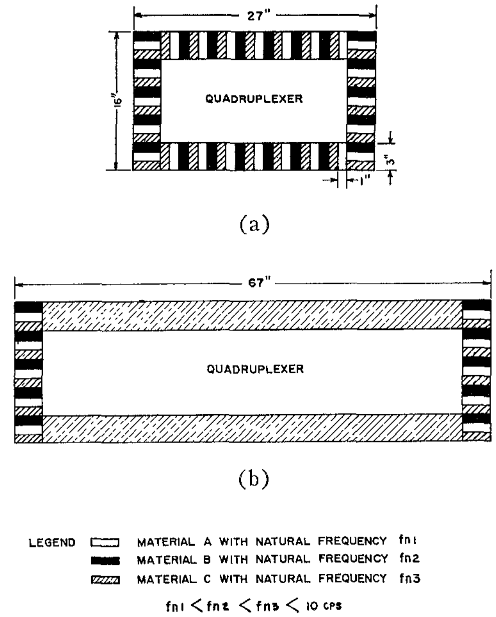


Fig. 12—Design concept of special packing case for the quadruplexer. (a) End cross section of quadruplexer packing case. (b) Longitudinal cross section of quadruplexer packing case.

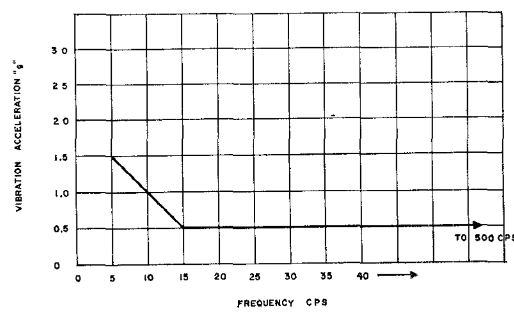


Fig. 13—Vibration acceleration vs frequency applied on quadruplexer during vibration tests on packing case.

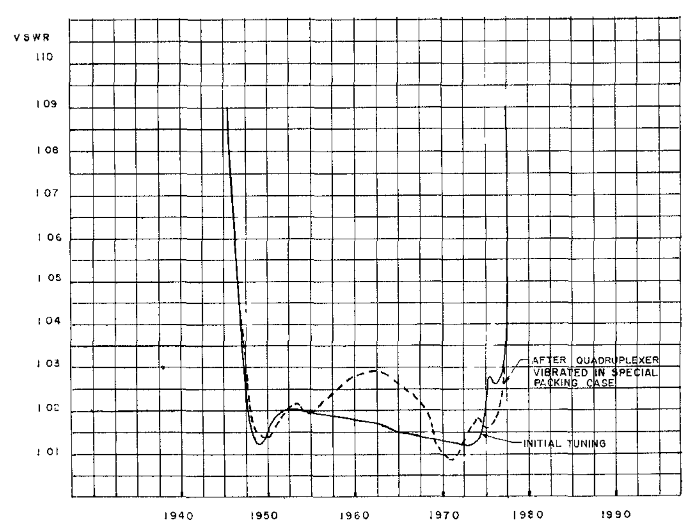


Fig. 14—Deterioration caused in filter tuning due to vibration.

Conclusion

The presented experimental data show that it is possible to connect four waveguide band-pass filters into a branching network which has an extremely low pass-band reflection coefficient. The various side effects of such a network (line length, filter proximity, junction effect) can be compensated by a proper coupling network and by the tuning possibilities of the filter sections themselves. After the basic problem is solved, the most important practical requirement for such a network is its independency from external parameters (terminal loading, temperature, vibration, shock). The elimination of these factors is possible, but requires particular design and an increase in cost relative to the conventional design.

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Some Recent Findings in Microwave Storage*

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Summary—**This paper describes an experimental investigation of frequency memory in a recirculating amplifier storage device. The objective of the investigation was to determine what mechanism caused injected energy to shift to preferred storage frequencies. Using fast-acting crystal switches, the output energy was selectively viewed, and it was found that the energy in any circulation when viewed separately was of the input frequency. The spectrum photographs which are included in the paper show that the recirculating amplifier when operating with an open loop gain greater than unity does not oscillate at preferred frequencies.**

Introduction

ALTHOUGH a complete historical search on the origin of RF storage has not been conducted, it appears that much of the early work can be attributed to L. M. Field, W. A. Edson, R. W. DeGrasse, and T. B. Warren of Stanford University. The work at Stanford resulted in memory devices capable of storing frequency for considerable periods of time. The need for such devices in military systems prompted continued development, and as a result, broad-band storage devices capable of reasonable storage times have been built.

The basic storage device, consisting of an amplifier and a delay line in a closed loop with appropriate input and output coupling devices, operates on a recirculating principle. An instruction pulse applied at the input is amplified by a TWT, delayed and attenuated by the delay line, and reamplified by the TWT. The TWT also supplies the limiting and suppression characteristics necessary for storage operation. Limiting is obtained by operating the TWT in the region of saturation where the gain vs power-in curve exhibits a negative slope; suppression is obtained from that characteristic of a saturated TWT or other limiter which in the presence of a strong signal exhibits a lower value of gain for a weaker signal than for the strong signal. Thus, when the storage system is operating with an open loop gain greater than unity, the limiting characteristic prevents the signal from increasing to an infinite magnitude and the suppression characteristic retards the build-up of unwanted signals such as noise.

The basic storage system as described above suffers two major limitations:

1) Storage time, the length of time an input signal can be stored before noise build-up takes over, is limited if very large bandwidths are considered.
2) Frequency accuracy, the amount of energy at the instruction frequency as compared to total energy in the system, may be low.

This report deals exclusively with the frequency-accuracy limitation. The treatment is limited to short storage times, 10 microseconds or less, and it is assumed that TWT and microwave component parameters are such that the necessary storage time is obtainable. Consistent with these assumptions, the reported data has

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