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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[3] P. Foldes and N. Gothard, "Synthesis of low-reflection waveguide joint systems," IRE Trans. on Microwave Theory and Techniques, vol. MTT-9, pp. 169–175; March, 1961.
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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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been taken at frequencies for which the system exhibited reasonable storage times. It will be shown that exact frequency storage can be achieved if the output energy is properly extracted from the loop.

Frequency Accuracy of a Storage Device

To be useful in most applications, a storage device must be capable of memorizing the frequency of the received signal. The advantages of a system capable of storing equally well all frequencies within the band of operation over a system capable of storing only at discrete frequencies is readily apparent. Thus, frequency accuracy when defined as the per cent of total output power within a given bandwidth centered about the input frequency can be used as a figure of merit for storage devices.

It has previously been thought that such a storage system as represented in Fig. 1 was capable of storing only at discrete frequencies.[1–3] This device, often described as a multimode oscillator when having an open loop gain greater than unity, operates on a recirculation principle. An instruction pulse applied at the input is amplified by the TWT, delayed and attenuated in the delay network and reapplied to the TWT input. If the instruction pulse width is made equal to the delay time of the delay network and the frequency is such that the total electrical length of the loop is an integral number of wavelengths, then each circulation is in phase and a concentration of energy at the input frequency is seen at the output. A typical spectrum photograph for this condition is shown in Fig. 2.

Next, consider that the instruction pulse width is again made equal to the delay time of the delay unit, but the input frequency is such that the total electrical length of the loop is an odd number of half wavelengths. Each circulation is now π radians out of phase with its neighboring circulation, and a spectrum photograph of such a condition (Fig. 3) shows the output energy to have shifted and to be concentrated at the frequencies for which the electrical length of the loop is an even number of half wavelengths.

For frequencies intermediately between the two cases sighted above, observations of the output always show a concentration of energy at those frequencies for which all circulations are in phase, with the greatest concentration of energy at the nearest such frequency. The frequencies at which the energy is concentrated are called preferred frequencies or preferred modes. The frequency spacing between preferred frequencies is determined by the delay in the loop and is given by $\Delta f = 1/\tau_0$, where τ_0 is the total delay time around the loop. It is generally interpreted that the system is oscillating at one or more of the preferred modes, and the output energy is concentrated at preferred frequencies.

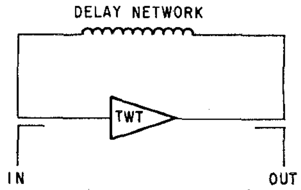


Fig. 1—Basic storage loop.

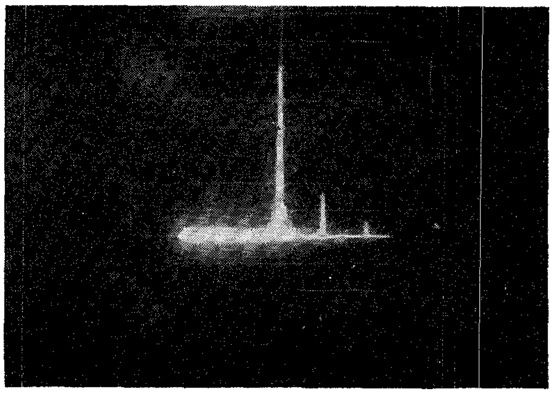


Fig. 2—Typical spectrum of 2 μsec of storage on a preferred frequency.

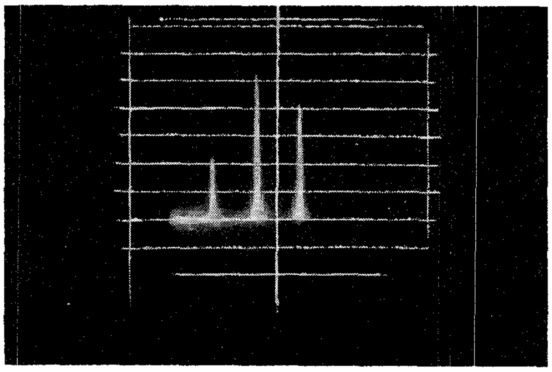


Fig. 3—Typical spectrum of 2 μsec of storage midway between preferred frequencies.

Adopting the viewpoint that a recirculating amplifier when operating with an open loop gain greater than unity oscillates at the nearest frequency for which a favorable phase shift exists (electrical length of loop an integral number of wavelengths), brings up some interesting questions. If the instruction pulse width is slightly less than the delay time of the delay network such that the circulations do not overlap each other, what mechanism causes oscillations to occur at preferred frequencies? How long after initiation of the instruction pulse do oscillations first appear? Does the energy at the instruction frequency shift suddenly or gradually to the preferred modes?

[1] W. A. Edson, "Frequency Memory in Multi-Mode Oscillators," Electronics Res. Lab., Stanford University, Stanford, Calif., Tech. Rept. No. 16; July 19, 1959.
[2] R. W. DeGrasse, "Stability of Multi-Mode Oscillatory Systems," Electronics Res. Lab., Stanford University, Stanford, Calif., Tech. Rept. No. 18; August 9, 1954.
[3] H. C. Lee, "Linear Analysis of Multi-Mode Oscillatory Systems," Electronics Res. Lab., Stanford University, Stanford, Calif., Tech. Rept. No. 20; July 26, 1954.

In view of recent improvements in high-speed crystal switches, it was felt that the answers to these questions could be obtained most readily from an experimental study of an actual storage device incorporating high-speed crystal switches.

Experimental Setup

Fig. 4 shows a block diagram of the experimental storage device used in this investigation. The storage loop consists of a TWT, a delay line, a crystal switch, input and output directional couplers, and a variable attenuator. Delay lines of both coaxial and waveguide variety were used as delay networks. The specific delay line used in the various tests will be noted.

The "loop gate" crystal switch, capable of rise and fall times of less than 10 nanoseconds, is used to gate the storage loop on for the desired storage time. The variable attenuator is used to adjust the loop loss and thus select the operating point of the TWT.

The instruction pulse is obtained by gating the output of a CW signal source with fast-rise time crystal switches. The output energy extracted by the 3-db directional coupler is passed through an "out gate" crystal switch and then fed to a spectrum analyzer, a narrow-band receiver, or a broad-band detector. The "out gate" switch is controlled in both its "on time" and its "time position" relative to the instruction pulse. Thus, any circulation can be viewed separately, or any number of circulations can be viewed together. Repetitive operation of the storage system, necessary for visual display, is obtained using the 1-kc sync source. The narrow-band receiver is used to monitor storage time within a fixed bandwidth about the instruction frequency, while the broad-band detector shows the energy in the entire bandwidth of the system as a function of time.

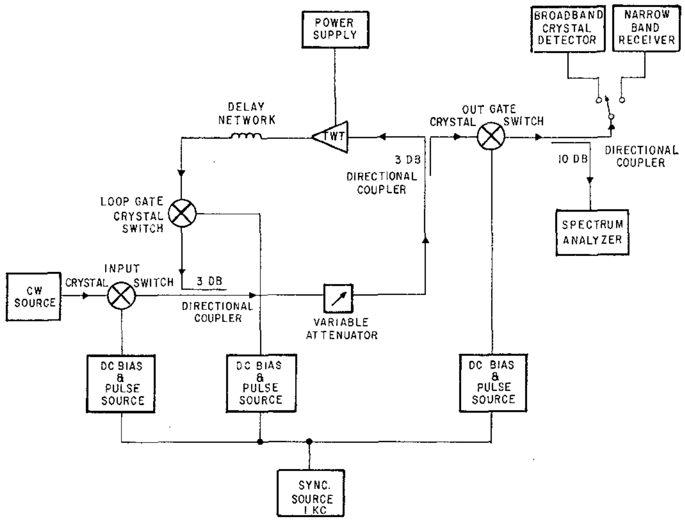


Fig. 4—Block diagram of experimental storage device.

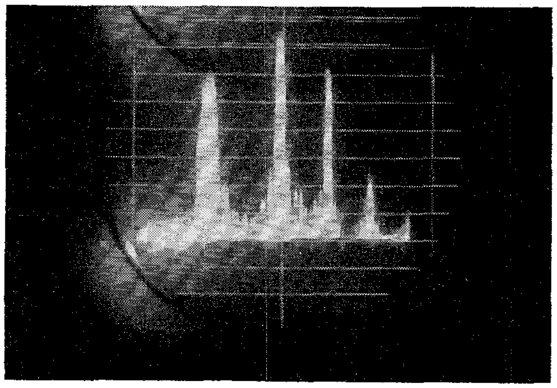


Fig. 5—Spectrum of 2 μsec of storage on a preferred frequency using waveguide delay line.

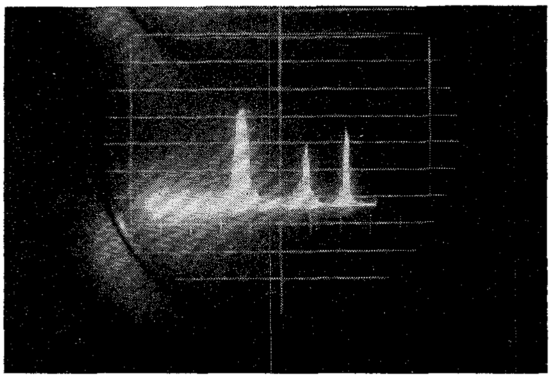


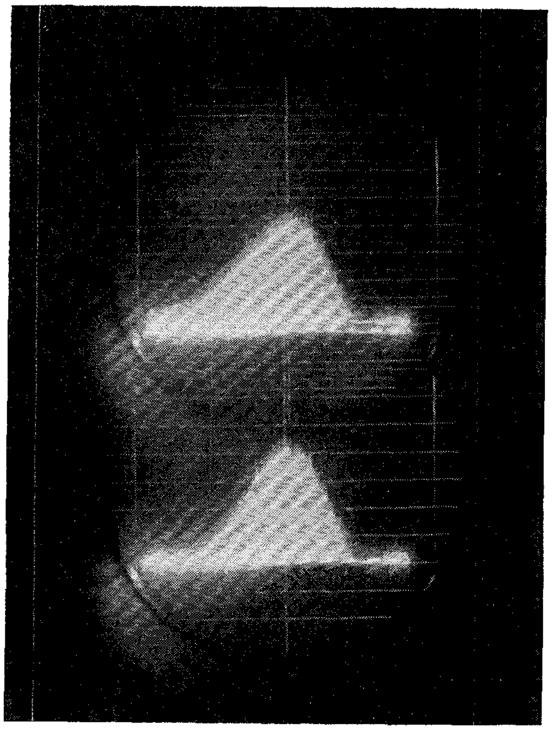
Fig. 6—Spectrum of 2 μsec of storage between preferred frequencies using waveguide delay line.

Experimental Findings

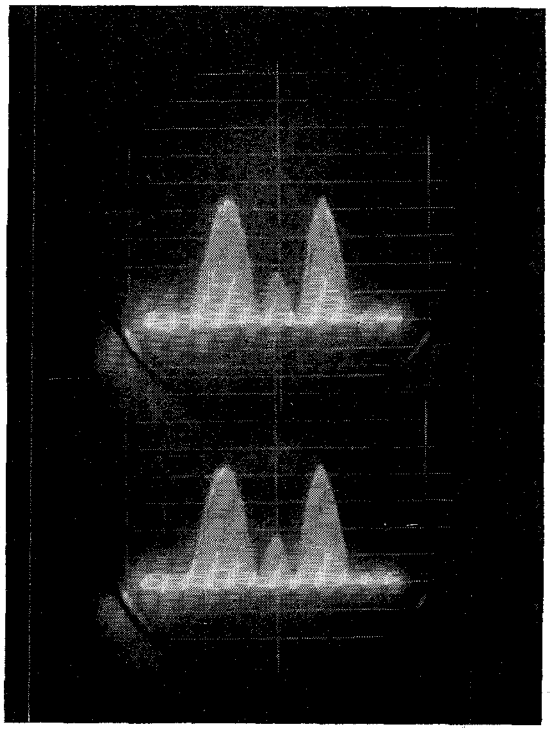
Using a waveguide delay line, an instruction pulse of width equal to the delay time of the loop was injected into the storage loop at a "preferred" frequency. With the "loop gate" adjusted for 10 microseconds of storage and the "out gate" adjusted for 2 microseconds (several circulations) of viewing, the spectrum photograph of Fig. 5 was obtained.

Next, using the same waveguide delay line, an instruction pulse of width equal to the delay time of the loop was injected into the storage loop at a frequency midway between two preferred frequencies. With the "loop gate" again adjusted for 10 microseconds of storage and the "out gate" again adjusted for 2 microseconds of viewing, the spectrum photograph of Fig. 6 was obtained.

To determine how the energy in the system shifted to the preferred mode, the "out gate" switch was adjusted to allow viewing of a single circulation. By moving the time position of the "out gate" switch through the storage period, it was observed that the energy in any circulation was always at the input frequency. Fig. 7 compares the spectrum of the first with the 47th circulation and the combination of the first, second, and third with the combination of the 45th, 46th and 47th circulations for the condition of instruction pulse width equal to the loop delay and input frequency midway between preferred frequencies. Fig. 8 shows the spectra

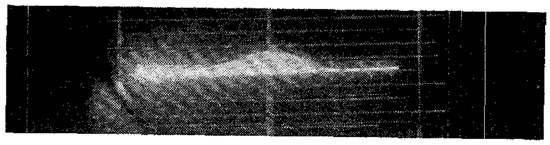


(a)

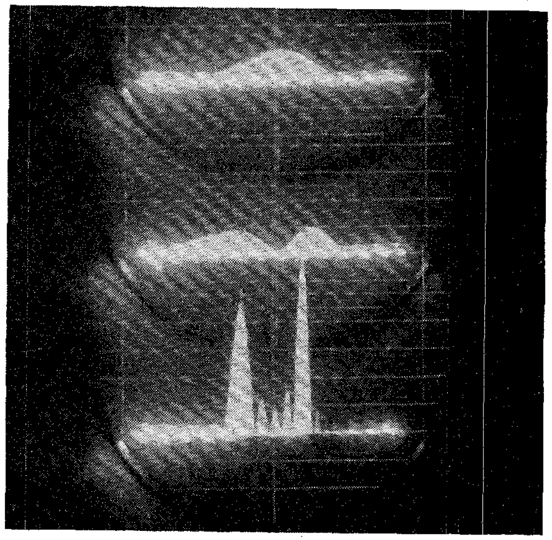


(b)

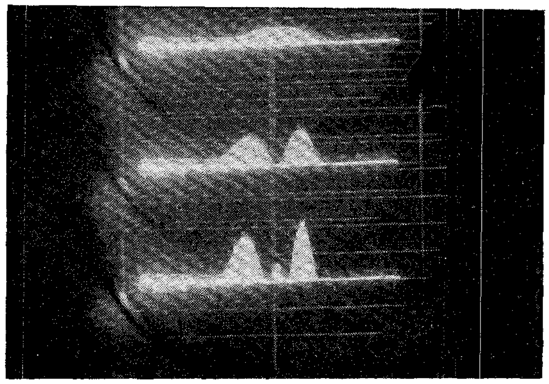
Fig. 7—Spectra showing various circulations during storage.



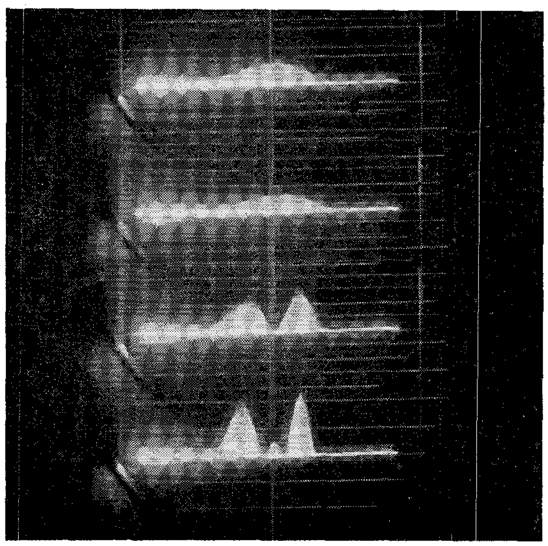
(a)



(b)



(c)



(d)

Fig. 8—Spectra showing various combinations of "out gate" width and time position.

obtained for various combinations of "out gate" width and time position again for the condition of the input frequency being midway between preferred frequencies. Fig. 8(a) shows the input signal; 8(b) the 1st circulation, 1st and 2nd, 1st through 5th; 8(c) the 7th circulation, 7th and 8th, 7th through 9th; 8(d) input signal, 14th circulation, 14th and 15th, 14th through 16th.

The waveguide delay line was replaced by a coaxial delay line. Further tests were conducted, and the results are shown in the following figures.

Fig. 9 shows the spectrum of a circulation 2 microseconds after initiation of storage tracking smoothly as the input frequency is varied. Fig. 10 shows a similar condition except the circulation being viewed is at 8 microseconds after initiation of storage.

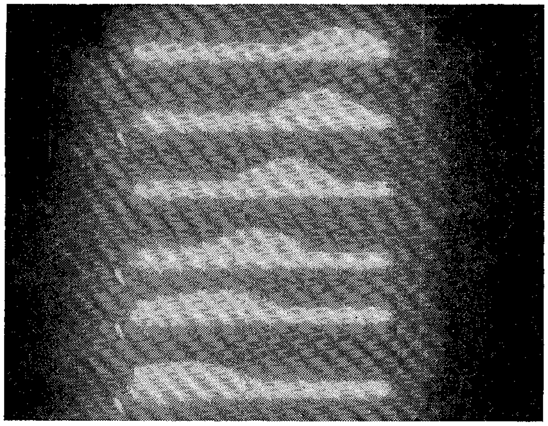


Fig. 9—Spectrum of a single circulation 2 μsec after initiation of storage.

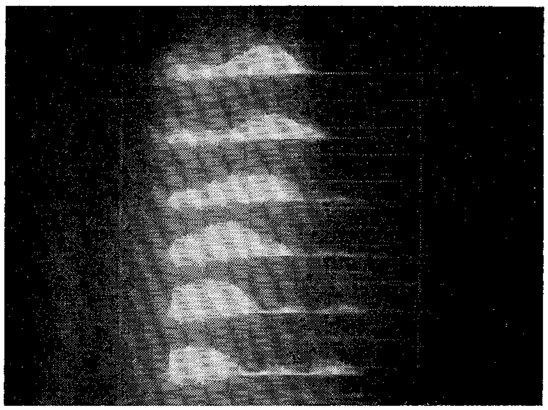


Fig. 10—Spectrum of a single circulation 8 μsec after initiation of storage.

Fig. 11 shows the spectrum of a single circulation viewed at 2, 4, 6, and 8 microseconds after initiation of storage for the condition of input frequency midway between preferred frequencies. Bottom spectrum shows input signal.

The effect of viewing two adjacent circulations under the condition of input frequency midway between preferred frequencies is shown in Fig. 12. Spectra from bottom to top are: input, 1st and 2nd, 3rd and 4th, 5th and 6th, 21st and 22nd. The circulations, both of fre-

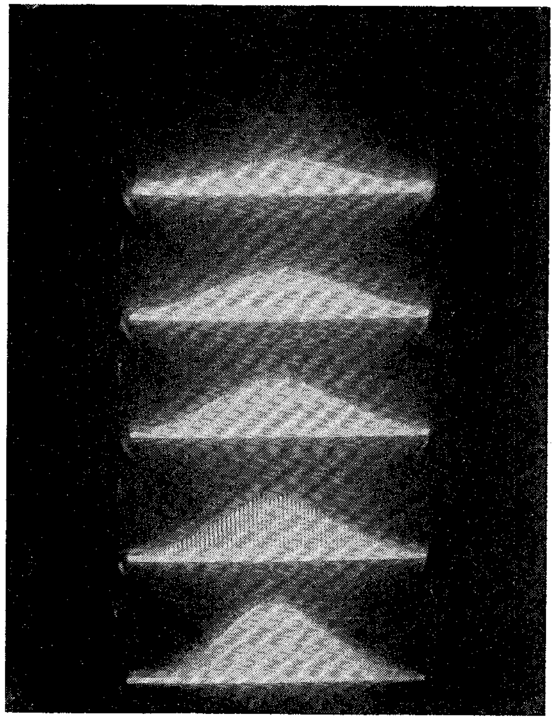


Fig. 11—Spectrum of single circulation at various times in the storage cycle.

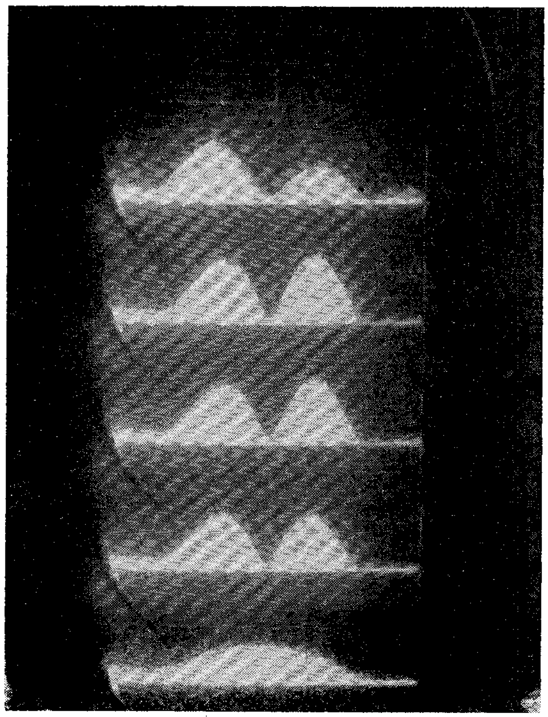


Fig. 12—Spectrum of two circulations.

quency f_0, are π radians out of phase with each other and when summed in the spectrum analyzer, produce a concentration of energy at frequency $f_0 \pm (3/8)1/\tau_0$, where τ_0 is the total time delay of the loop. Notice that there is no energy at the input frequency f_0. Since these results, especially the $\pm(3/8)1/\tau_0$ spacing, were other than expected, a Fourier analysis was conducted. In the analysis, given in the Appendix, a Fourier integral formulation is used to obtain the envelope of the power spectrum. The power spectrum obtained from the analysis displays peaks at $\pm(3/8)1/\tau_0$, as shown in Fig. 13, and thus verifies the experimental findings.

Since the viewing of two circulations gave $(3/4)1/\tau_0$ separation between power spectrum peaks, and the viewing of several circulations resulted in a $1/\tau_0$ separation between peaks, an additional test was conducted to observe the intermediate steps. As can be seen in Fig. 14, as more circulations are viewed, the peaks of energy concentration move outward to the $1/\tau_0$ spacing.

It is interesting to note that although there is no energy at the input frequency when an even number of circulations are viewed, as in Fig. 14, there is energy at the input frequency when an odd number of circulations are viewed, as shown in Figs. 7 and 8.

Conclusions

After examining the experimental results, it can be concluded that the RF storage system described in this report does not oscillate in the true sense of the word, but rather operates on a recirculating amplifier principle. The concentration of energy at the preferred frequencies results only from the summing process in the receiver of the spectrum analyzer when several circulations of various phases are viewed. Thus, a short-time RF storage system consisting of a fixed delay line, a TWT, and appropriate input and output coupling devices is capable of exact frequency storage *if the output energy is properly extracted.*

It can also be concluded that pulse spreading, known to occur in the TWT and delay line, although a possible cause for multimode oscillations in a long-time storage device, is not of sufficient magnitude to disturb the short-time storage of a recirculating amplifier.

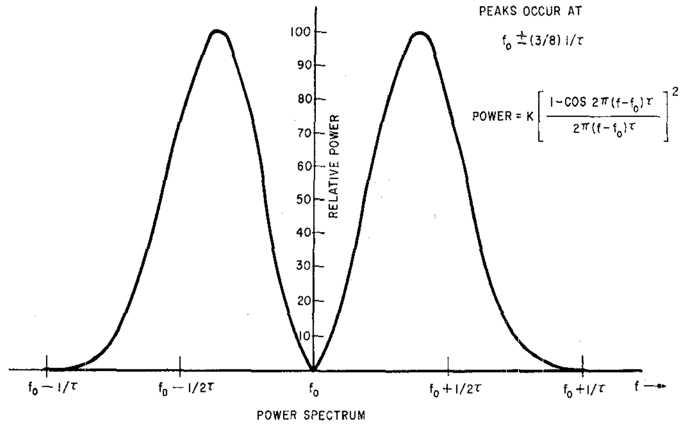


Fig. 13—Power spectrum obtained by Fourier analysis.

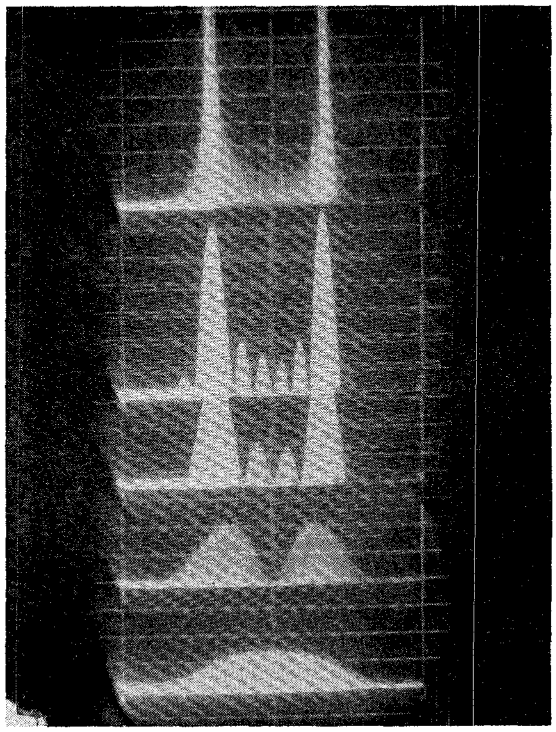


Fig. 14—Spectra showing peaks of energy concentration moving from (3/4) $1/\tau_0$ to $1/\tau_0$ separation.

Appendix

Fourier Analysis

The following analysis was performed to obtain the power spectrum and, in particular, the frequency separation between power peaks for a train of pulses where a single pulse has the waveform shown in Fig. 15. The waveform is made up of two sine waves of carrier frequency f_0 but differing in phase by π radians.

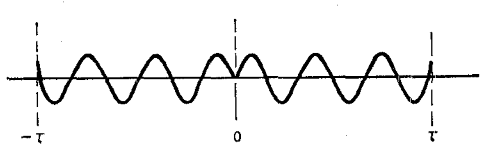


Fig. 15.

The function is described by:

$$f(t) = -A \sin \omega_0 t \qquad -T \leq t \leq 0$$
$$f(t) = A \sin \omega_0 t \qquad 0 \leq t \leq T$$
$$f(t) = 0 \qquad |t| > T.$$

The envelope of the harmonics of the train of pulses is readily obtained from a Fourier integral formulation of a single pulse.

The Fourier transform of the function $f(t)$[4,5] is given by

$$g(\omega) = \frac{1}{2\pi}\int_{-\infty}^{\infty} f(t)e^{-j\omega t}dt, \tag{1}$$

where $g(\omega)$ describes the spectral density of the waveform. Substituting $f(t)$ for the waveform shown above, (1) becomes

$$g(\omega) = -\frac{1}{2\pi}\int_{-\tau}^{0} A \sin \omega_0 t e^{-j\omega t}dt + \frac{1}{2\pi}\int_{0}^{\tau} A \sin \omega_0 t e^{-j\omega t}dt. \tag{2}$$

Substituting $e^{-j\omega t} = \cos \omega t - j \sin \omega t$ and integrating yields

$$g(\omega) = \frac{A}{2\pi}\left[\frac{1-\cos(\omega_0-\omega)\tau}{(\omega_0-\omega)} + \frac{1-\cos(\omega_0+\omega)\tau}{(\omega_0-\omega)}\right]. \tag{3}$$

[4] J. A. Stratton, "Electromagnetic Theory," 1st ed., McGraw-Hill Book Co., Inc., New York, N. Y.; 1941.

[5] L. A. Pipes, "Applied Mathematics for Engineers and Physicists," 2nd ed., McGraw-Hill Book Co., Inc., New York, N. Y.; 1958.

Eq. (3) can be simplified by neglecting the term containing $(\omega_0+\omega)$ in the denominator and defining a new term α by $\omega = \omega_0 \pm \alpha$ where $\alpha \ll \omega_0$. Thus (3) becomes

$$g(\omega) = \frac{A}{2\pi}\,\frac{1-\cos(\pm\alpha)\tau}{(\pm\alpha)}. \tag{4}$$

The power spectrum is given by

$$(g(\omega))^2 = \left[\frac{A}{2\pi}\right]^2\left[\frac{1-\cos(\pm\alpha)\tau}{(\pm\alpha)}\right]^2. \tag{5}$$

Multiplying numerator and denominator by τ, (5) becomes

$$(g(\omega))^2 = \left(\frac{A\tau}{2\pi}\right)^2\left[\frac{1-\cos(\pm\alpha)\tau}{(\pm\alpha)\tau}\right]^2. \tag{6}$$

Eq. (6) displays power peaks at $\alpha \approx \pm 3/4\pi/\tau$, as shown in Fig. 13. While actual differentiation of (6) yields power peaks at $\alpha = \pm 0.741\ \pi/\tau$, for purposes of this report, the approximation of $3/4\pi/\tau$ will be used.

ACKNOWLEDGMENT

The author would like to thank R. Stickney and D. Khouri for their effort in obtaining the experimental data, S. N. Miller for his initial investigation into the pulse analysis, and Dr. C. E. Faflick for valuable suggestions and supervision.

Excess Noise in Microwave Detector Diodes*

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***Summary*—The dependence of available excess noise in type 1N26 microwave crystal-diode rectifiers on applied microwave power was measured. This may be approximated by a power law with constants characteristic of the particular crystal. As a consequence of the dependence of both excess noise and dc rectified power on input-power level, there is a level which minimizes the ratio of these quantities. Similarly, in the case of a modulated microwave carrier there is an input level which minimizes the ratio of excess noise to demodulated power, and so provides optimum detection of small modulation.**

I. Introduction

THE NOISE in excess of kT_0B resulting from application of microwave power to a crystal detector is important in many applications of microwaves. It is interesting in itself to know the functional dependence of the excess noise on the input microwave power and the variation of excess noise with change in the various parameters that may be varied. Furthermore, in order to determine operating conditions that result in optimum video detection of signals of specified RF power and modulation factor, it is necessary to know the dependence of both detected signal and excess noise on these parameters. These considerations find direct application in systems dealing with small amplitude, low-frequency modulation on relatively large microwave signals—for example, in detection of Zeeman or Stark modulation in microwave spectroscopy and parmagnetic resonance, or in certain stabilization systems for microwave oscillators in which error modulation is placed on a microwave signal by a stabilizing element such as a reference cavity.

When a crystal diode is used as a detector of microwave power, the average operating point $(\bar{e}, \bar{\imath})$ that results is a point in the current voltage plane that cannot be reached by application of dc voltages to the crystal. Thus, the excess noise produced by application of microwave signals on a crystal detector cannot be

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† National Bureau of Standards, Boulder, Colo.