Experiments on the Regeneration of Binary Microwave Pulses

By O. E. DeLANGE

(Manuscript received September 7, 1955)

A simple device has been produced for regenerating binary pulses directly at microwave frequencies. To determine the capabilities of such devices one of them was included in a circulating test loop in which pulse groups were passed through the device a large number of times. Results indicate that even in the presence of serious noise and bandwidth limitations pulses can be regenerated many times and still show no noticeable deterioration. Pictures of circulated pulses are included which illustrate performance of the regenerator.

INTRODUCTION

The chief advantage of a transmission system employing binary pulses resides in the possibility of regenerating such pulses at intervals along the route of transmission to prevent the accumulation of distortion due to noise, bandwidth limitations and other effects. This makes it possible to take the total allowable deterioration of signal in each section of a long relay system rather than having to make each link sufficiently good to prevent total accumulated distortion from becoming excessive. This has been pointed out by a number of writers.[1-2]

W. M. Goodall[3] has shown the feasibility of transmitting television signals in binary form. Such transmission requires a considerable amount of bandwidth; a seven digit system, for example, would require transmission of seventy million pulses per second. This need for wide bands makes the microwave range an attractive one in which to work. S. E. Miller[4] has pointed out that a binary system employing regeneration might prove to be especially advantageous in waveguide transmission.

---

[1] B. M. Oliver, J. R. Pierce and, C. E. Shannon, The Philosophy of PCM, Proc. I. R. E., Nov., 1948.

[2] L. A. Meacham and E. Peterson, An Experimental Multichannel Pulse Code Modulation System of Toll Quality, B. S. T. J., Jan. 1948.

[3] W. M. Goodall, Television by Pulse Code Modulation, B. S. T. J., Jan., 1951.

[4] S. E. Miller, Waveguide as a Communication Medium, B. S. T. J., Nov., 1954.

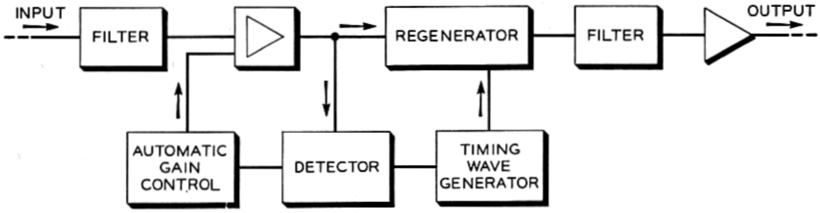

Fig. 1 — A typical regenerative repeater shown in block form.

That the Bell System is interested in the long-distance transmission of television and other broad-band signals is evident from the number of miles of such broad-band circuits, both coaxial cable and microwave radio,[5] now in service. These circuits provide high-grade transmission because each repeater was designed to have a very flat frequency characteristic and linear phase over a considerable bandwidth. Furthermore, these characteristics are very carefully maintained. For a binary pulse system employing regeneration the requirements on flatness of band and linearity of phase can be relaxed to a considerable degree. The components for such a system should, therefore, be simpler and less expensive to build and maintain. Reduced maintenance costs might well prove to be the chief virtue of the binary system.

Since the chief advantage of a binary system lies in the possibility of regeneration it is obvious that a very important part of such a system is the regenerative repeater employed. Fig. 1 shows in block form a typical broad-band, microwave repeater. Here the input, which might come from either a radio antenna or from a waveguide, is first passed through a proper microwave filter then amplified, probably by a traveling-wave amplifier. The amplified pulses of energy are regenerated, filtered, amplified and sent on to the next repeater. The experiment to be described here deals primarily with the block labeled "Regenerator" on Fig. 1.

In these first experiments one of our main objectives was to keep the repeater as simple as possible. This suggests regeneration of pulses directly at microwave frequency, which for this experiment was chosen to be 4 kmc. It was suggested by J. R. Pierce and W. D. Lewis, both of Bell Telephone Laboratories, that further simplification might be made possible by accepting only partial instead of complete regeneration. This suggestion was adopted.

For the case of complete regeneration each incoming pulse inaugurates a new pulse, perfect in shape and correctly timed to be sent on to the

---

[5] A. A. Roetken, K. D. Smith and R. W. Friis, The TD-2 System, B. S. T. J., Oct., 1951, Part II.

next repeater. Thus noise and other disturbing effects are completely eliminated and the output of each repeater is identical to the original signal which entered the system. For the case of partial regeneration incoming pulses are retimed and reshaped only as well as is possible with simple equipment. Obviously the difference between complete and partial regeneration is one of degree.

One object of the experiment was to determine how well such a partial regenerator would function and what price must be paid for employing partial instead of complete regeneration. The regenerator developed consists simply of a waveguide hybrid junction with a silicon crystal diode in each side arm. It appears to meet the requirement of simplicity in that it combines the functions of amplitude slicing and pulse retiming in one unit. A detailed description of this unit will be given later. Although the purpose of this experiment was to determine what could be accomplished in a very simple repeater we must keep in mind that superior performance would be obtained from a regenerator which approached more nearly the ideal. For some applications the better regenerator might result in a more economical system even though the regenerator itself might be more complicated and more expensive to produce.

METHOD OF TESTING

The regeneration of pulses consists of two functions. The first function is that of removing amplitude distortions, the second is that of restoring each pulse to its proper time. The retiming problem divides into two parts the first of which is the actual retiming process and the second that of obtaining the proper timing pulses with which to perform this function. In a practical commercial system timing information at a repeater would probably be derived from the incoming signal pulses. There are a number of problems involved in this recovery of timing pulses. These are being studied at the present time but were avoided in the experiment described here by deriving such information from the local synchronizing gear.

Since the device we are dealing with only partially regenerates pulses it is not enough to study the performance of a single unit — we should like to have a large number operating in tandem so that we can observe what happens to pulses as they pass through one after another of these regenerators. To avoid the necessity of building a large number of units the pulse circulating technique of simulating a chain of repeaters was employed. Fig. 2 shows this circulating loop in block form.

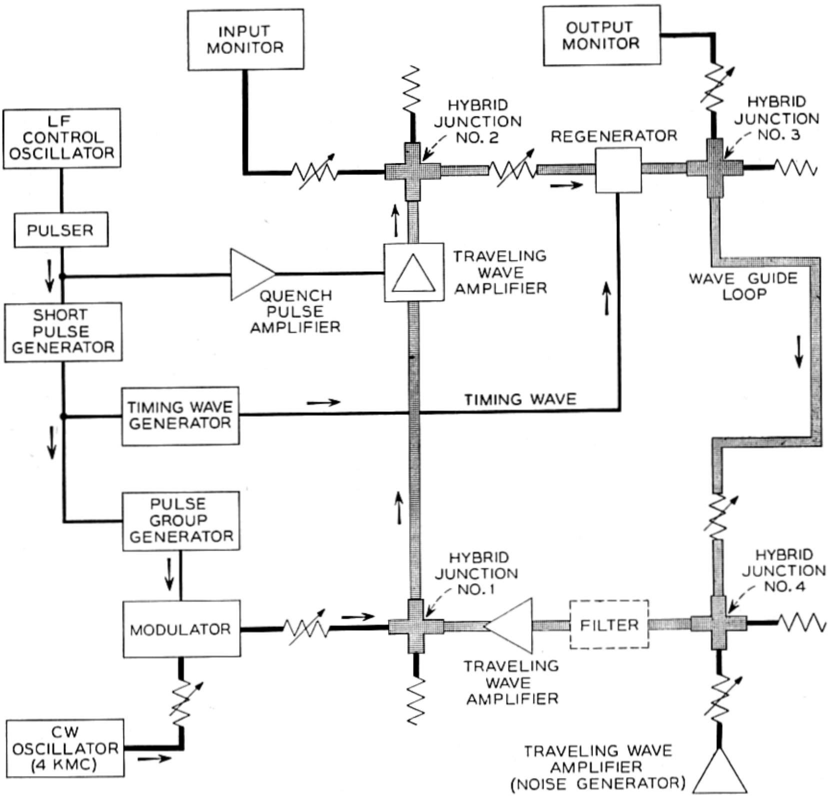

Fig. 2 — The circulating loop.

To provide RF test pulses for this loop the output of a 4 kmc, cw oscillator is gated by baseband pulse groups in a microwave gate or modulator. The resultant microwave pulses are fed into the loop (heavy line) through hybrid junction No. 1. They are then amplified by a traveling-wave amplifier the output of which is coupled to the pulse regenerator through another hybrid junction (No. 2). The purpose of this hybrid is to provide a position for monitoring the input to the regenerator. A monitoring position at the output of the regenerator is provided by a third hybrid, the main output of which feeds a considerable length of waveguide which provides the necessary loop delay. At the far end of the waveguide another hybrid (No. 4) makes it possible to feed noise, which is derived from a traveling-wave amplifier, into the loop. The combined output after passing through a band pass filter is amplified by another traveling-wave amplifier and fed back into the loop input thus completing the circuit.

The synchronizing equipment starts out with an oscillator going at approximately 78 kc. A pulse generator is locked in step with this oscillator. The output of the pulser is a negative 3 microsecond pulse as shown in Fig. 3A. After being amplified to a level of about 75 volts this pulse is applied to the helix of the first traveling-wave tube to reduce the gain of this tube during the 3-microsecond interval. Out of each 12.8μsec interval pulses are allowed to circulate for 9.8μsec but are blocked for the remaining 3μsec thus allowing the loop to return to the quiescent condition once during each period as shown on Figs. 3A and 3C.

The 3μsec pulse also synchronizes a short-pulse generator. This unit delivers pulses which are about 25 millimicroseconds long at the base and spaced by 12.8μsec, i.e., with a repetition frequency of 78 kc. See Fig. 3B.

In order to simulate a PCM system it was decided to circulate pulse

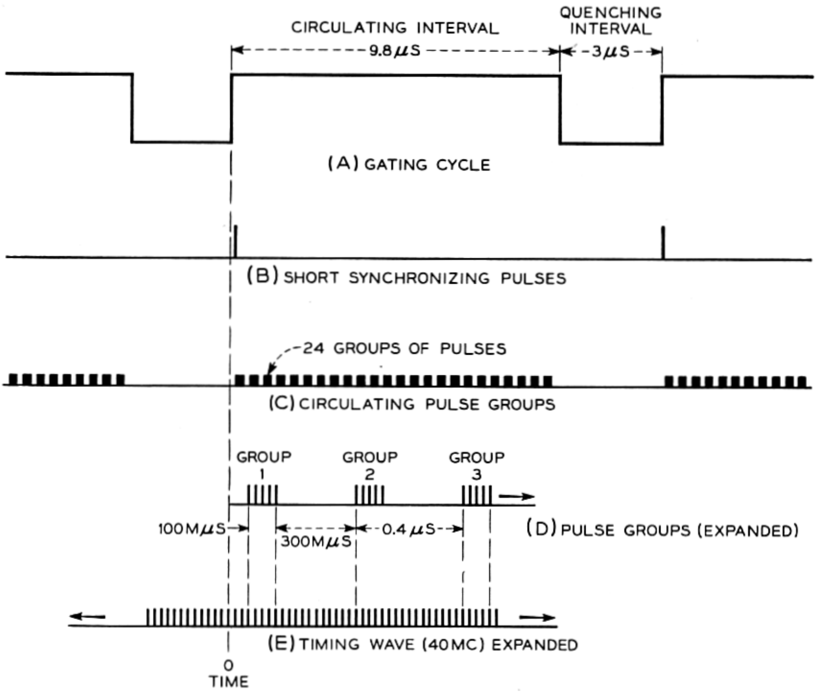

Fig. 3 — Timing events in the circulating loop.

groups rather than individual pulses through the system. These were derived from the pulse group generator which is capable of delivering any number up to 5 pulses for each short input pulse. These pulses are about 15 milli-microseconds long at the base and spaced 25 milli-microseconds apart. The amplitude of each of these pulses can be adjusted independently to any value from zero to full amplitude making it possible to set up any combination of the five pulses. These are the pulses which are used to gate, or modulate, the output of the 4-kmc oscillator.

The total delay around the waveguide loop including TW tubes, etc., was 0.4μsec or 400 milli-microseconds. This was sufficient to allow time between pulse groups and yet short enough that groups could circulate 24 times in the available 9.8μsec interval. This can be seen from Figs. 3C and 3D. The latter figure shows an expanded view of circulating pulse groups. The pulses in Group 1 are inserted into the loop at the beginning of each gating cycle, the remaining groups result from circulation around the loop.

When all five pulses are present in the pulse groups the pulse repetition frequency is 40 mc. (Pulse interval 25 milli-microseconds). For this condition timing pulses should be supplied to the regenerator at the rate of 40 million per second. These pulses are supplied continuously and not in groups as is the case with the circulating pulses. See Fig. 3E. In order to maintain time coincidence between the circulating pulses and the timing pulses the delay around the loop must be adjusted to be an exact multiple of the pulse spacing. In this experiment the loop delay is equal to 16-pulse intervals. Since timing pulses are obtained by harmonic generation from the quenching frequency as will be discussed later this frequency must be an exact submultiple of pulse repetition frequency. In this experiment the ratio is 512 to 1.

Although the above discussion is based on a five-pulse group and 40-mc repetition frequency it turned out that for most of the experiments described here it was preferable to drop out every other pulse, leaving three to a group and resulting in a 20-mc repetition frequency. The one exception to this is the limited-band-width experiment which will be described later.

For all of the experiments described here timing pulses were derived from the 78-kc quenching frequency by harmonic generation. A pulse with a width of 25 milli-microseconds and with a 78-kc repetition frequency as shown in Fig. 3B supplied the input to the timing wave generator. This generator consists of several stages of limiting amplifiers all tuned to 20 mc, followed by a locked-in 20-mc oscillator. The output of the amplifier consists of a train of 20-mc sine waves with constant amplitude for most of the 12.8μsec period but falling off somewhat at the end of the period. This train locks in the oscillator which oscillates at a constant amplitude over the whole period and at a frequency of 20 mc. Timing pulses obtained from the cathode circuit of the oscillator tube provided the timing waves for most of the experiments. For the experiment where a 40-mc timing wave was required it was obtained from the 20 mc train by means of a frequency doubler. For this case it is necessary for the output of the timing wave generator to remain constant in amplitude and fixed in phase for the 512-pulse interval between synchronizing pulses.

In spite of the stringent requirements placed upon the timing equipment it functioned well and maintained synchronism over adequately long periods of time without adjustment.

PERFORMANCE OF REGENERATOR

Performance of the regenerator under various conditions is recorded on the accompanying illustrations of recovered pulse envelopes. The first experiment was to determine the effects of disturbances which arise at only one point in a system. Such effects were simulated by adding disturbances along with the group of pulses as they were fed into the circulating loop from the modulator. This is equivalent to having them occur at only the first repeater of the chain.

Some of the first experiments also involved the use of extraneous pulses to represent noise or distortion since these pulses could be synchronized and thus studied more readily than could random effects. In Fig. 4A the first pulse at the left represents a desired digit pulse with its amplitude increased by a burst of noise, the second pulse represents a clean digit pulse, and the third pulse a burst of noise. This group is at the input to the regenerator. Fig. 4B shows the same group of pulses after traversing the regenerator once. The pulses are seen to be shortened due to the gating, or retiming, action. There is also seen to be some amplitude correction, i.e. the two desired pulses are of more nearly the same amplitude and the undesired pulse has been reduced in relative amplitude. After a few trips through the regenerator the pulse group was rendered practically perfect and remained so for the rest of the twenty-four trips around the loop. Fig. 4C shows the group after 24 trips. In another experiment pulses were circulated for 100 trips without deterioration. Nothing was found to indicate that regeneration could not be repeated indefinitely.

Figs. 5A and 5B represent the same conditions as those of 4A and 4B

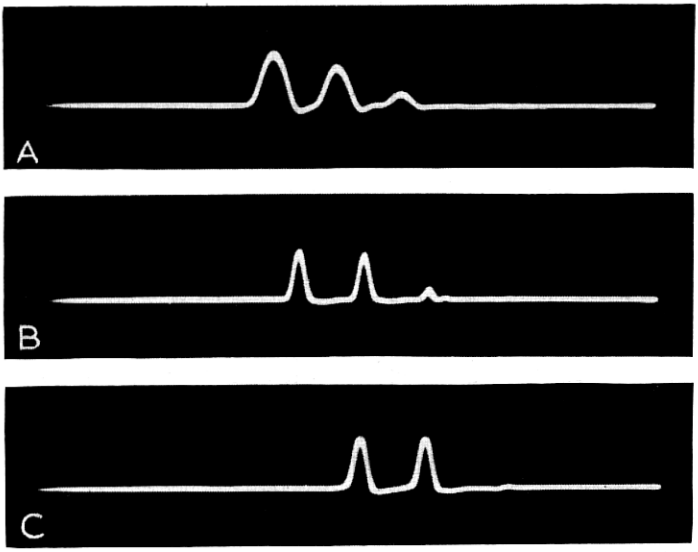

Fig. 4 — Effect of regeneration on disturbances which occur at only one repeater. A — Input to regenerator, original signal. B — Output of regenerator, first trip. C — Output of regenerator, 24th trip.

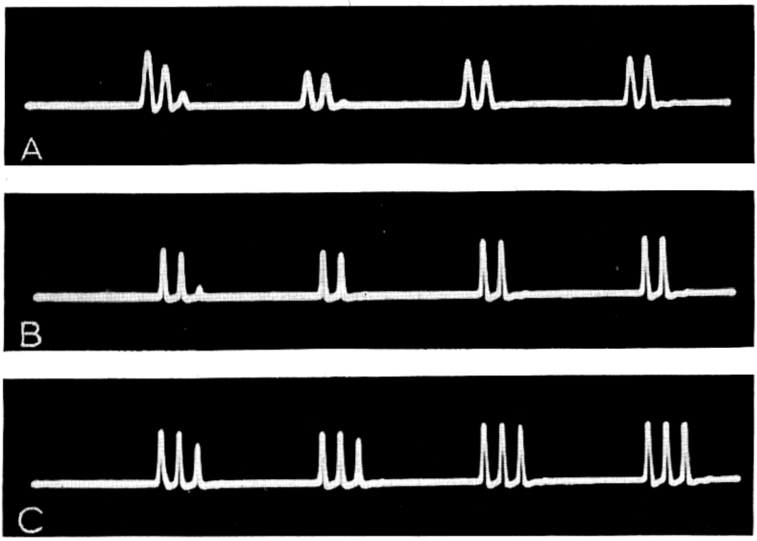

Fig. 5 — Effect of regeneration on disturbances which occur at only one repeater. A — Input to regenerator, first four groups. B — Output of regenerator, first four groups. C — Output of regenerator, increased input level.

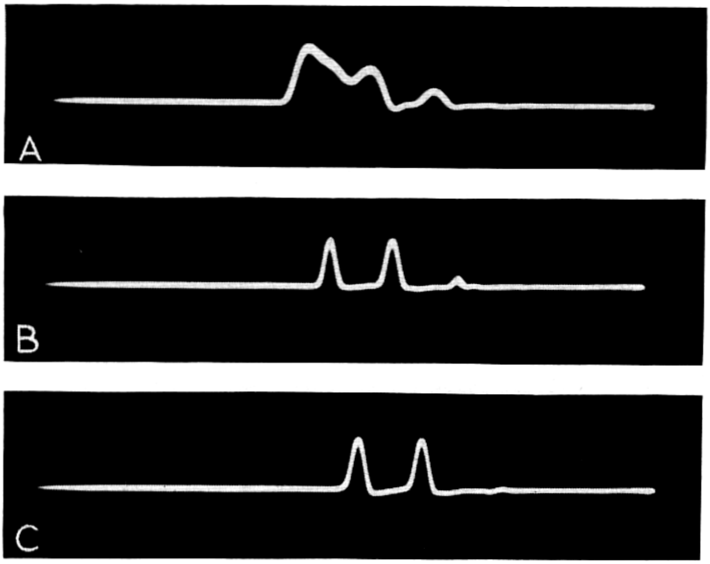

Fig. 6 — Effect of regeneration on disturbances which occur at only one repeater. A — Input to regenerator, original signal. B — Output of regenerator, first trip. C — Output of regenerator, 24th trip.

except that the oscilloscope sweep has been contracted in order to show the progressive effects produced by repeated passage of the signal through the regenerator. Fig. 5B shows that after the pulses have passed through the regenerator only twice all visible effects of the disturbances have been removed. Fig. 5C shows the effect of simply increasing the RF pulse input to the regenerator by approximately 4 db. The small "noise" pulse which in the previous case was quickly dropped out because of being below the slicing level has now come up above the slicing level and so builds up to full amplitude after only a few trips through the regenerator. Note that in the cases shown in Figs. 4 and 5 discrimination against unwanted pulses has been purely on an amplitude basis since the gate has been unblocked to pulses with amplitudes above the slicing level whenever one of these disturbing pulses was present.

For Fig. 6A conditions are the same as for Fig. 4A except that an additional pulse has been added to simulate intersymbol noise or interference. Fig. 6B indicates that after only one trip through the regenerator the effect of the added pulse is very small. After a few trips the effect is completely eliminated leaving a practically perfect group which continues on for 24 trips as shown by Fig. 6C. For the intersymbol pulse, discrimination is on a time basis since this interference occurs at a time

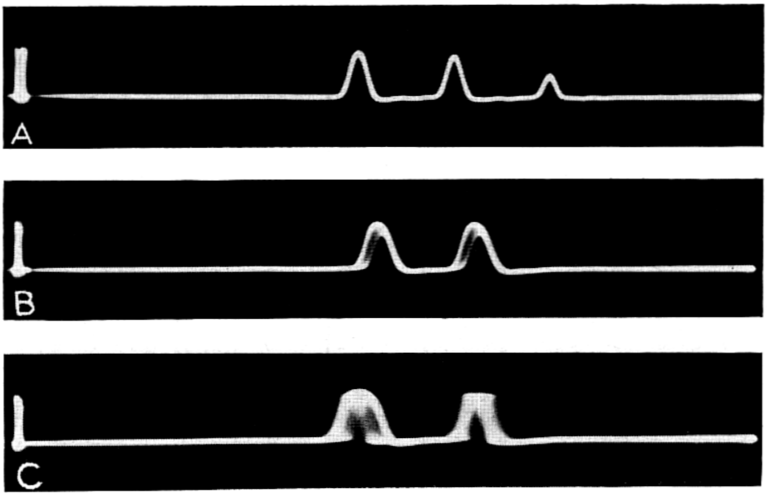

Fig. 7 — Effect of regenerating in amplitude without retiming. A — Output of regenerator, no timing, firt trip. B — Output of regenerator, no timing, 10th trip. Output of regenerator, no timing, 23rd trip.

when no gating pulse is present and hence finds the gate blocked regardless of amplitude.

To show the need for retiming the pictures shown on Figs. 7 and 8 were taken. These were taken with the amplitude slicer in operation but with the pulses not being retimed. Figs. 7A, 7B and 7C, respectively, show the output of the slicer for the first, tenth and twenty-third trips. After ten trips, there is noticeable time jitter caused by residual noise in the system; after 23 trips this jitter has become severe though pulses are still recognizable. It should be pointed out that for this experiment no noise was purposely added to the system and hence the signal-to-noise ratio was much better than that which would probably be encountered in an operating system. For such a system we would expect time jitter effects to build up much more rapidly. For Fig. 8 conditions are the same as for Fig. 7 except that the pulse spacing is decreased by the addition of an extra pulse at the input. Now, after ten trips, time jitter is bad and after 23 trips the pulse group has become little more than a smear. This increased distortion is probably due to the fact that less jitter is now required to cause overlap of pulses. There may also be some effects due to change of duty cycle. For Fig. 9 there was neither slicing nor retiming of pulses. Here, pulse groups deteriorate very rapidly to nothing more than blobs of energy. Note that there is an increase of

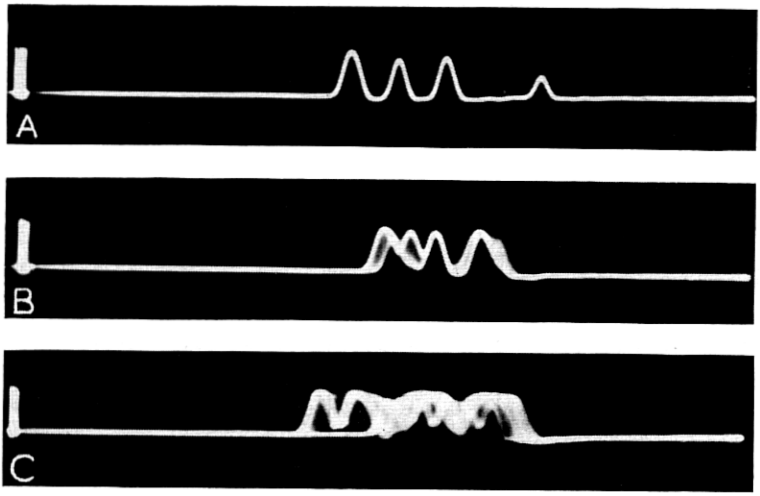

Fig. 8 — Effect of regenerating in amplitude without retiming. A — Output of regenerator, no timing, first trip. B — Output of regenerator, no timing, 10th trip. C — Output of regenerator, no timing, 23rd trip.

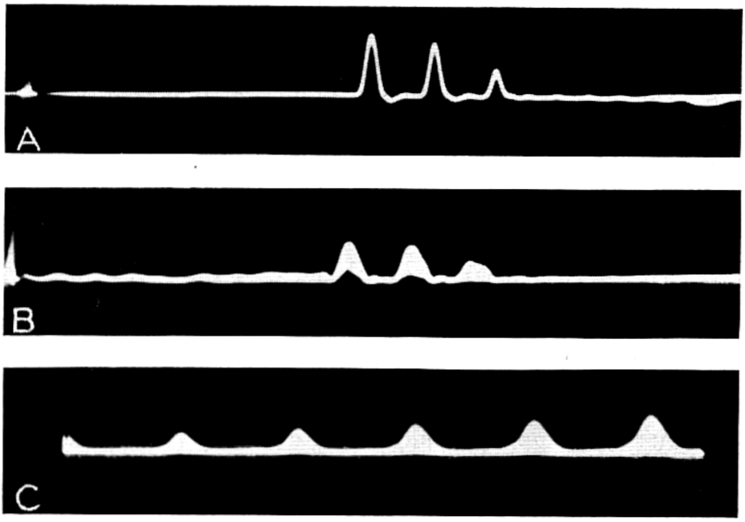

Fig. 9 — Pulses circulating through the loop without regeneration. A — Original input. B — 4th trip without regeneration. C — 20th to 24th trip without regeneration.

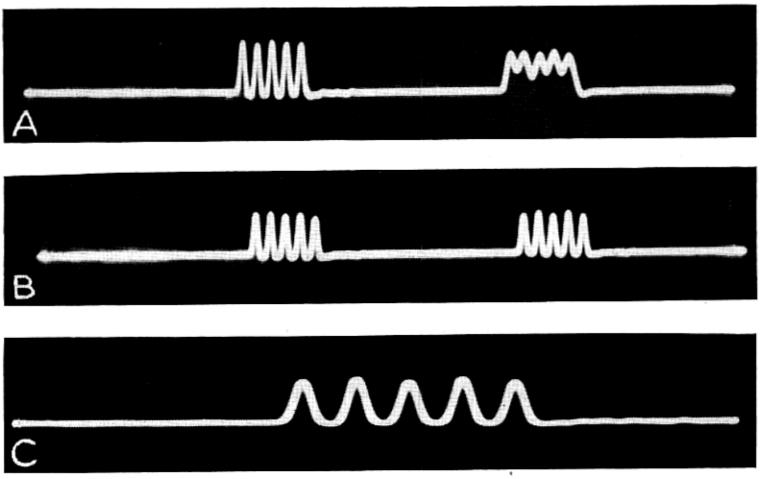

Fig. 10 — The regeneration of band-limited pulses. A — Input to regenerator, first two groups. B — Output of regenerator, first two groups. C — Output of regenerator, 24th trip.

amplitude with each trip around the loop indicating that loop gain was slightly greater than unity. Without the slicer it is difficult to set the gain to exactly unity and the amplitude tends to either increase or decrease depending upon whether the gain is greater or less than unity. Results indicated by the pictures of Fig 9 are possibly not typical of a properly functioning system but do show what happened in this particular system when regeneration was dispensed with.

Another important function of regeneration is that of overcoming band-limiting effects. Figs. 10 and 11 show what can be accomplished. For this experiment the pulse groups inserted into the loop were as shown at the left in Fig. 10A. These pulses were 15 milli-microseconds wide at the base and spaced by 25 milli-microseconds which corresponds to a repetition frequency of 40 mc. After passing through a band-pass filter these pulses were distorted to the extent shown at the right in Fig. 10A. From the characteristic of the filter, as shown on Fig. 12, it is seen that the bandwidth employed is not very different from the theoretical minimum required for double sideband transmission. This minimum characteristic is shown by the dashed lines on Fig. 12. Fig. 10B shows that at the output of the regenerator the effects of band limiting have been removed. This is borne out by Fig. 10C which shows that after 24 trips the code group was still practically perfect. It should be pointed out that the pulses traversed the filter once for each trip around the loop,

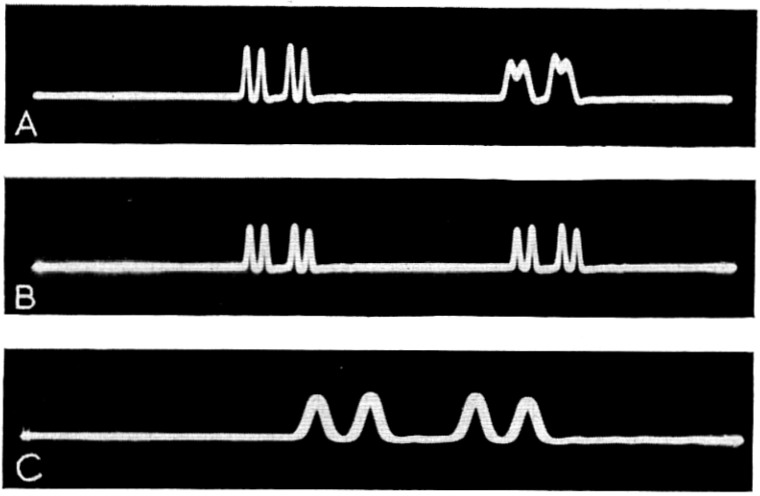

Fig. 11 — The regeneration of band-limited pulses. A — Input to regenerator, first two groups. B — Output of regenerator, first two groups. C — Output of regenerator, 24th trip.

that is for each trip the input to the regenerator was as shown at the right of Fig. 10A and the output as shown by Fig. 10B. It is important to note that Fig. 12 represents the frequency characteristic of a single link of the simulated system. The pictures of Fig. 11 show the same experiment but this time with a different code group. Any code group which we could set up with our five digit pulses was transmitted equally well.

In order to determine the breaking point of the experimental system, broad-band noise obtained from a traveling-wave amplifier was added into the system as shown on Fig. 2. The breaking point of the system is the noise level which is just sufficient to start producing errors at the output of the system.* The noise is seen to be band-limited in exactly the same way as the signal. With the system adjusted to operate properly the level of added noise was increased to the point where errors became barely discernible after 24 trips around the loop. Noise level was now reduced slightly (no errors discernible) and the ratio of rms signal to rms noise measured. Fig. 13A shows the input to the regenerator for the 23rd and 24th trips with this amount of noise added. Note that the noise has

---

* The type of noise employed has a Gaussian amplitude distribution and therefore there was actually no definite breaking point — the rate at which errors occurred increased continuously as noise amplitude was increased. The breaking point was taken as the noise level at which errors became barely discernible on the viewing oscilloscope. More accurate measurements made in other experiments indicate that this is a fairly satisfactory criterion.

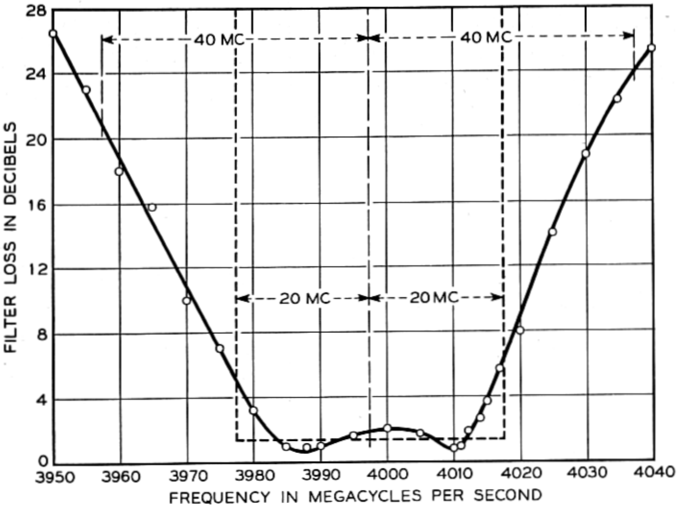

Fig. 12 — Characteristics of the band-pass microwave filter.

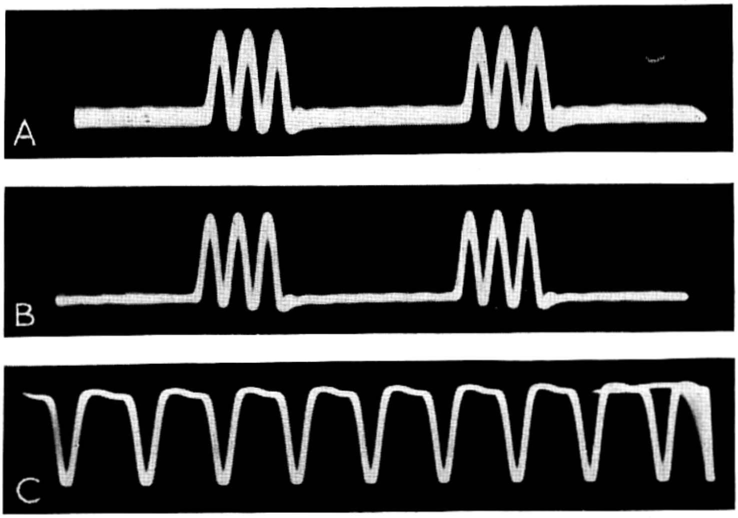

Fig. 13. — The regeneration of pulses in the presence of broad-band, random noise added at each repeater. A — Input to regenerator, 23rd and 24th trips, broad-band noise added. B — Input to regenerator, 23rd and 24th trips, no added noise. C — 20-mc timing wave.

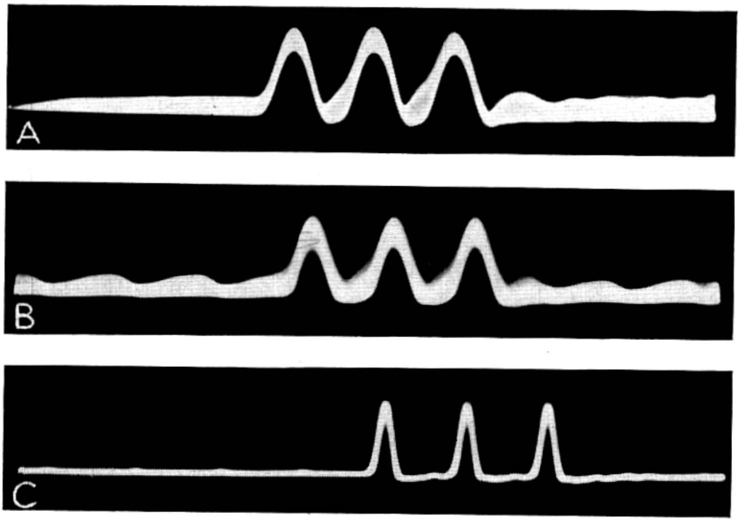

Fig. 14 — The regeneration of pulses in the presence of interference occurring at each repeater. A — Original signal with added modulated carrier interference. B — Input to regenerator, 24th trip, modulated carrier interference. C — Output of regenerator, 24th trip, modulated carrier interference.

produced a considerable broadening of the oscilloscope trace. Fig. 13B shows the same pulse groups with no added noise. These photographs are included to give some idea as to how bad the noise was at the breaking point of the system. Of course maximum noise peaks occur rather infrequently and do not show on the photograph. At the output of the regenerator effects due to noise were barely discernible. This output looked so much like that shown at Fig. 14C that no separate photograph is shown for it.

Figs. 14A, 14B and 14C show the effects of a different type of interference upon the system. This disturbance was produced by adding into the system a carrier of exactly the same frequency as the signal carrier (4 kmc) but modulated by a 14-mc wave, a frequency in the same order as the pulse rate. Here again the level of the interference was adjusted to be just below the breaking point of the system. A comparison between Figs. 14B and 14C gives convincing evidence that the regenerator has substantially restored the waveform.

For the case of the interfering signal a ratio of signal to interference of 10 db on a peak-to-peak basis was measured when the interference was just below the breaking point of the system. This, of course, is 4 db above the theoretical value for a perfect regenerator. For the case of broad-band random noise an rms signal to noise ratio of 20 db was measured.* This compares with a ratio of 18 db as measured by Messrs. Meacham and Peterson for a system employing complete regeneration and a single repeater.†

Recently, A. F. Dietrich repeated the circulating loop experiment at a radio frequency of 11 kmc. His determinations of required signal-to-noise ratios are substantially the same as those reported here. From the various experiments we conclude that for a long chain of properly functioning regenerative repeaters of the type discussed here practically perfect transmission is obtained as long as the signal-to-noise ratio at the input to each repeater is 20 db or better on an rms basis. In an operating system it might be desirable to increase this ratio to 23 db to take care of deficiencies in automatic gain controls, power changes, etc.

From the experiments we also conclude that the price we pay for using partial instead of complete regeneration is about 3 to 4 db increase in the required signal-to-noise ratio. In a radio system which provides a fading margin this penalty would be less since the probability that two or more adjacent links will reach maximum fades simultaneously is very small. Under these conditions only one repeater at a time would be near the breaking point and the system would behave much as though the repeater provided complete regeneration.

TIMING

Although we have considered the problem of retiming of signal pulses up to now we have not discussed the problem of obtaining the necessary timing pulses to perform this function, but have simply assumed that a source of such pulses was available. As was mentioned earlier timing pulses would probably be derived from the signal pulses in a practical system. These pulses would be fed into some narrow band amplifier tuned to pulse repetition frequency. The output of this circuit could be made to be a sine wave at repetition frequency if gaps between the input pulses were not too great. Timing pulses could be derived from this sine wave. This timing equipment could be similar to that used in these experiments and described earlier. Further study of the problems of obtaining timing information is being made.

---

* For Gaussian noise it is not possible to specify a theoretical value of minimum S/N ratio without specifying the tolerable percentage of errors. For the number of errors detectable on the oscilloscope it seems rasonable to assume a 12 db peak factor for the noise. The peak factor for the signal is 3 db. The 6 db peak S/N which would be required for an ideal regenerator then becomes 15 db on an rms basis.

† L. A. Meacham and E. Peterson, B. S. T. J., p. 43, Jan., 1948.

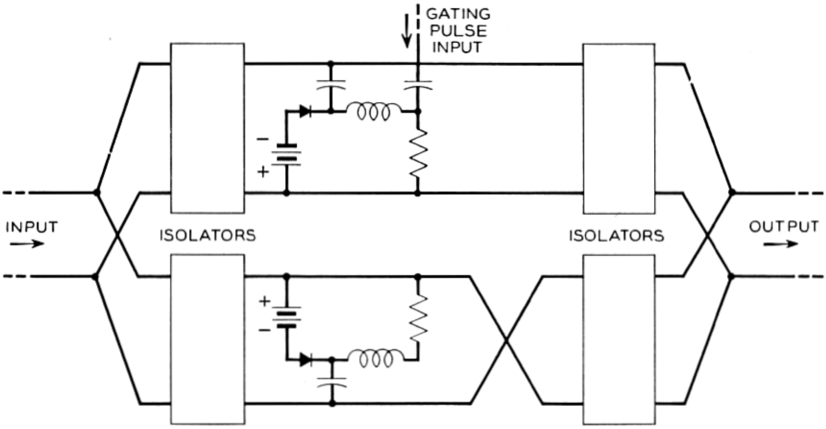

Fig. 15A — Low-frequency equivalent of the partial regenerator.

DESCRIPTION OF REGENERATOR

This device regenerates pulses by performing on them the operations of "slicing" and retiming.

An ideal slicer is a device with an input-output characteristics such as shown by the dashed lines of Fig. 15C. It is seen that for all input levels below the so-called slicing level transmission through the device is zero but that for all amplitudes greater than this value the output level is finite and constant. Thus, all input voltages which are less than the slicing level have no effect upon the output whereas all input voltages greater than the slicing level produce the same amplitude of output. Normally conditions are adjusted so that the slicing level is at one-half

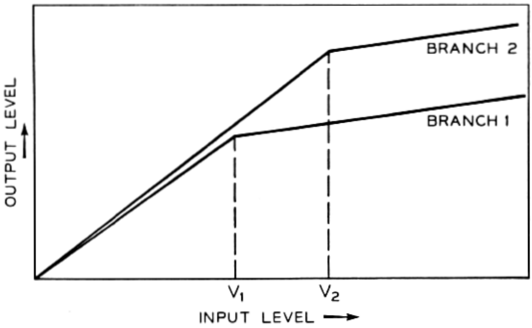

Fig. 15B — Characteristics of the separate branches with differential bias.

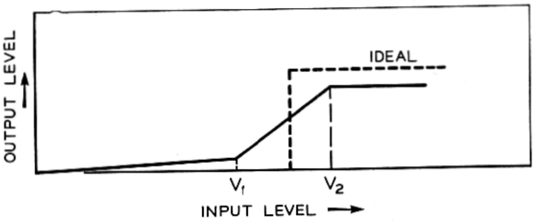

Fig. 15C — Resultant output with differential bias.

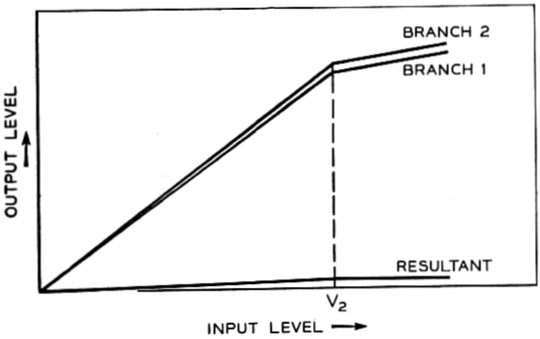

Fig. 15D — Characteristics of the separate branches and resultant output with equal biases.

of peak pulse amplitude — then at the output of the slicer there will be no effect whatsoever from disturbances unless these disturbances exceed half of the pulse amplitude. It is this slicing action which removes the amplitude effects of noise. Time jitter effects are removed by retiming, i.e., the device is made to have high loss regardless of input level except at those times when a gating pulse is present.

Fig. 15A shows schematically a low-frequency equivalent of the regenerator used in these experiments. Here an input line divides into two identical branches isolated from each other and each with a diode shunted across it. The outputs of the two branches are recombined through necessary isolators to form a single output. The phase of one branch is reversed before recombination, so that the final output is the difference between the two individual outputs.

Fig. 15B shows the input-output characteristics of the two branches when the diodes are biased back to be non-conducting by means of bias voltages V_1 and V_2 respectively. For low levels the input-output characteristic of both branches will be linear and have a 45° slope. As soon as the input voltage in a branch reaches a value equal to that of the back bias the diode will start to conduct, thus absorbing power and decrease the slope of the characteristic. The output of Branch 1 starts to flatten off when the input reaches the value V_1, while the output of Branch 2 does not flatten until the input reaches the value V_2. The combined output, which is equal to the differences of the two branch outputs, is then that shown by the solid line of Fig. 15C and is seen to have a transition region between a low output and a high output level. If the two branches are accurately balanced and if the signal voltage is large compared to the differential bias $V_2 - V_1$ the transition becomes sharp and the device is a good slicer.

If the two diodes are equally biased as shown on Fig. 15D the outputs of the two branches should be nearly equal regardless of input and the total output, which is the difference between the two branch outputs, will always be small.

Fig. 16 shows a microwave equivalent of the circuit of Fig. 15A. In the microwave structure lengths of wave-guide replace the wire lines and branching, recombining and isolation are accomplished by means of hybrid junctions. The hybrid shown here is of the type known as the 1A junction.

Fig. 17 shows another equivalent microwave structure employing only one hybrid. This is the type used in the experiments described here. The output consists of the combined energies reflected from the two side arms of the junction. With the junction connected as shown phase relationships are such that the output is the difference between the reflec-

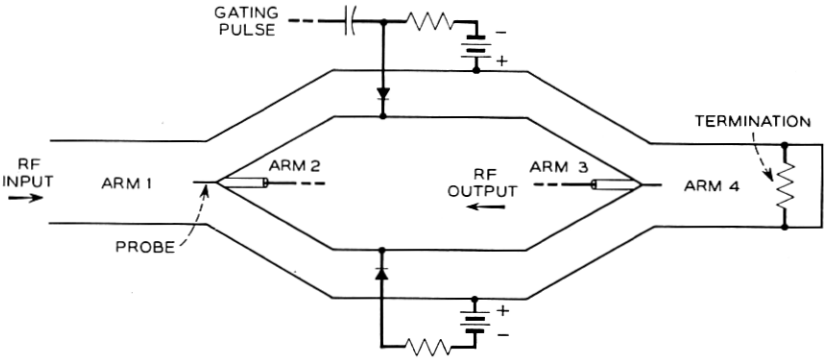

Fig. 16 — Microwave regenerator.

tions from the two side arms so that when conditions in the two arms are identical there is no output. The crystal diodes coupled to the side arms are equivalent to those shunted across the two lines of Fig. 15A.

Fig. 18, which is a plot of the measured input-output characteristic of the regenerator used in the loop test, shows how the device acts as a combined slicer and retimer. Curve A, obtained with equal biases on the two diodes, is the characteristic with no gating pulse applied i.e. the diodes are normally biased in this manner. It is seen that this condition produces the maximum of loss through the device. By shifting one diode bias so as to produce a differential of 0.5 volt the characteristic changes to that of Curve B. This differential bias can be supplied by the timing pulse in such a way that this pulse shifts the characteristic from that shown at A to that shown at B thus decreasing the loss through the device by some 12 to 15 db during the time the pulse is present. In this way the regenerator is made to act as a gate — though not an ideal one.

We see from curve B that with the differential bias the device has the characteristic of a slicer — though again not ideal. For lower levels of input there is a region over which the input-output characteristic is square law with a one db change of input producing a two db change of output. This region is followed by another in which limiting is fairly pronounced. At the 8-db input level, which is the point at which limiting sets in, the loss through the regenerator was measured to be approximately 12 db. The characteristic shown was found to be reproducible both in these experiments at 4 kmc and in those by A. F. Dietrich at 11 kmc.

For a perfect slicer only an infinitesimal change of input level is re-

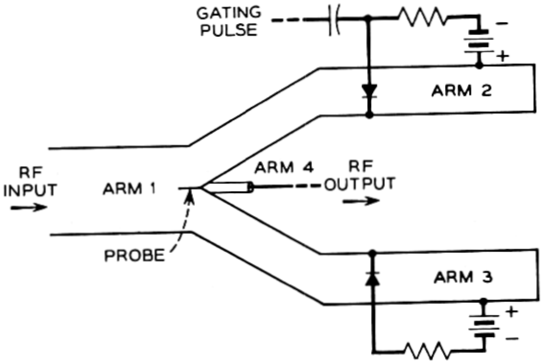

Fig. 17 — Microwave regenerator employing a single hybrid junction.

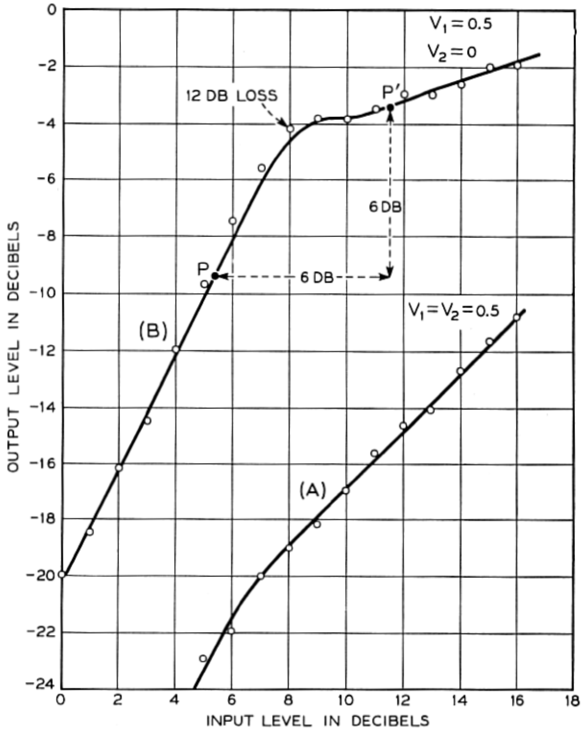

Fig. 18 — Static characteristics of the regenerator employed in these experiments.

quired to change the output from zero to maximum. The input level at which this transition takes place is the slicing level and has a very definite value. For a characteristic such as that shown on Fig. 18 this point is not at all definite and the question arises as to how one determines the slicing level for such a device. Obviously this point should be somewhere on the portion of the characteristic where expansion takes place. In the case of the circulating loop the slicing level is the level for which total gain around the loop is exactly equal to unity. Why this is so can be seen from Fig. 19 which is a plot of gain versus input level for a repeater containing a slicer with a characteristic as shown by curve B of Fig. 18. Amplifiers are necessary in the loop to make up for loss through the regenerator and other components. For Fig. 19 we assume that these amplifiers have been adjusted so that gain around the loop is exactly unity for an input pulse having a peak amplitude corresponding to the

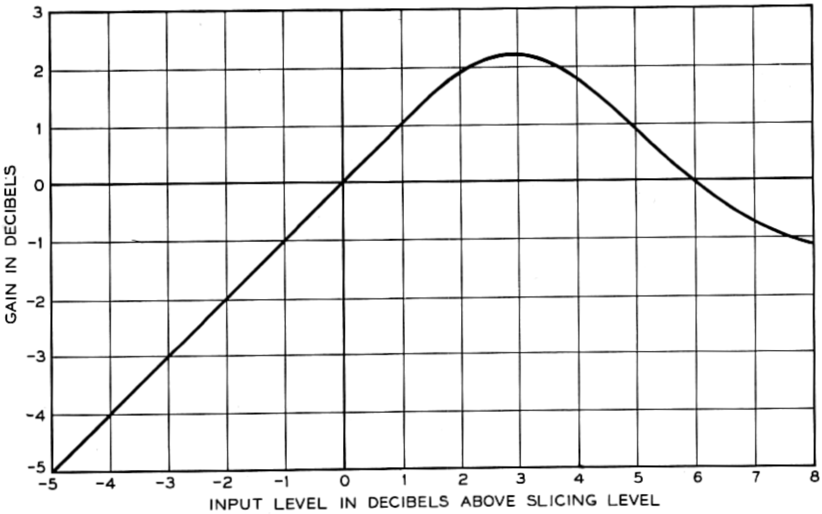

Fig 19 — Gain characteristics of a repeater providing partial regeneration.

point P' of Fig. 18. On Fig. 19 all other levels are shown in reference to this unity-gain value.

From Fig. 19 it is obvious that a pulse which starts out in the loop with a peak amplitude exactly equal to the reference, or slicing level, will continue to circulate without change of amplitude since for this level there is unity gain around the loop. A pulse with amplitude greater than the slicing level will have its amplitude increased by each passage through a regenerator until it eventually reaches a value of +6 db. It will continue to circulate at this amplitude, for here also the gain around the loop is unity.* Any pulse with peak amplitude less than the reference level will have its amplitude decreased by successive trips through the regenerator and eventually go to zero. We also see that the greater the departure of the amplitude of a pulse from the slicing level the more effect the regenerator has upon it. This means that the device acts much more powerfully on low level noise than on noise with pulse peaks near the slicing level. As examples consider first the case of noise peaks only 1 db below slicing level at the input (peak $S/N = 7$ db). At this level there is a 1 db loss through the repeater so that at the output the noise peaks will be 2 db below reference to give a S/N ratio of 8 db. Next

---

* Note that the +6-db level is at a point of stable equilibrium whereas at the slicing level equilibrium is unstable.

consider noise with a peak level 5 db below slicing level ($S/N = 11$ db) at the input. The loss at this level is 5 db resulting in a noise level 10 db below reference to give a S/N ratio of 16 db. We see that a 4 db improvement in S/N ratio at the input results in an 8 db improvement in this ratio at the output.

Everything which was said above concerning the circulating loop applies equally to a chain of identical repeaters. To set the effective slicing level at half amplitude at each repeater in a chain one would first find two points on the slicer characteristics such as P and P' of Fig. 18. The point P should be in the region of expansion and P' in the limiting region. Also the points should be so chosen that a 6 db increase of input from that at point P results in a 6 db increase in output at the point P'. If now at each repeater we adjust pulse peak amplitude at the slicer input to a value corresponding to that at point P' we will have unity gain from one repeater to the next at levels corresponding to pulse peaks. We will also have unity gain at levels corresponding to one half of pulse amplitude. The effective slicing level is thus set at half amplitude. Obviously the procedure for setting the slicing level at some value other than half amplitude would be practically the same. It should be pointed out that although half amplitude is the preferred slicing level for baseband pulses this is not the case for carrier pulses. W. R. Bennett of Bell Telephone Laboratories has shown that for carrier pulses the probability that noise of a given power will reduce signal pulses below half amplitude is less than the probability that this same noise will exceed half amplitude. This comes about from the fact that for effective cancellation there must be a 180° phase relationship between noise and pulse carrier. For this reason the slicing level should be set slightly above half amplitude for a carrier pulse system.

The difference in performance between a perfect slicer and one with characteristics such as shown on Fig. 18 are as follows: For the perfect slicer no effects from noise or other disturbances are passed from one repeater to the next. For the case of the imperfect regenerator some effects are passed on and so tend to accumulate in a chain of repeaters. To prevent this accumulated noise from building up to the breaking point of the system it is necessary to make the signal-to-noise ratio at each repeater somewhat better than that which would be required with the ideal slicer. For the case of random noise the required S/N ratio seems to be about 5 or 6 db above the theoretical value. This is due in part to slicer deficiency and in part to other system imperfections.

CONCLUSIONS

It is possible to build a simple device for regenerating pulses directly at microwave frequencies. A long chain of repeaters employing this regenerator should perform satisfactorily as long as the rms signal-to-noise ratio at each repeater is maintained at a value of 20 db or greater. There are a number of remaining problems which must be solved before we have a complete regenerative repeater. Some of these problems are: (1) Recovery of information for retiming from the incoming pulse train; (2) Automatic gain or level control to set the slicing level at each repeater; (3) Simple, reliable, economical, broad-band microwave amplifiers. (4) Proper filters — both for transmitting and receiving. Traveling-wave tube development should eventually result in amplifiers which will meet all of the requirements set forth in (3) above. Any improvements which can be made in the regenerator without adding undue complications would also be advantageous.

ACKNOWLEDGMENTS

A. F. Dietrich assisted in setting up the equipment described here and in many other ways. The experiment would not have been possible without traveling-wave tubes and amplifiers which were obtained through the cooperation of M. E. Hines, C. C. Cutler and their associates. I wish to thank W. M. Goodall, and J. R. Pierce for many valuable suggestions.