Broadband Oscilloscope Tube

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By applying traveling wave tube principles to the design of a helix type vertical deflection system it has become possible to build an oscilloscope tube whose bandwidth characteristic is flat over 600 megacycles. The trace on the fluorescent screen is readable without other optical means. The tube construction is similar to commercial cathode ray tubes, the only exception being that the alignment of the various tube elements has a closer tolerance. In actual use this tube allows one to view directly repetitive pulses a few millimicroseconds in width.

I. INTRODUCTION

New transmission systems which employ binary pulses and regeneration[1] require pulses which are a few millimicroseconds in length. One of the primary characteristics of short pulses is the wide bandwidths required for any system which is to handle them. The advantages of using a wideband system have been discussed by others[2, 3] and in this paper we will describe an oscilloscope which is capable of presenting a visual display for these millimicrosecond pulses.

In a conventional oscilloscope which uses a pair of plates to deflect the electron beam the frequency range is limited to the extent that a typical tube might have a response which is down by 3 db at 60 mc. This bandwidth is limited by the transit time of the electrons through the deflection system. This time interval should be short as compared to the period of the RF voltage on the plates. We can decrease the time with a resulting increase in bandwidth by shortening the axial length of the plates and increasing the speed of the electrons. Both of these factors, however, tend to decrease the sensitivity which we define as the deflection of the beam measured in units of spot diameters for a unit input voltage. A much improved method of overcoming the transit-time problem has been suggested by Pierce[4] where he uses a slow traveling RF wave to deflect the beam. The deflecting voltage travels at the same speed as the electrons and consequently a given electron sees the same phase of the wave throughout the deflection system. The bandwidth in such a system is now limited by the frequency range over which the RF structure is capable of propagating a wave at a constant velocity. This extends the frequency limit well into the microwave region. This principle has recently been used by Germeshausen[5] in a tube which displays single pulses or transient responses of very short duration.

The oscilloscope discussed here, shown in Figs. 1 and 2, has a flat

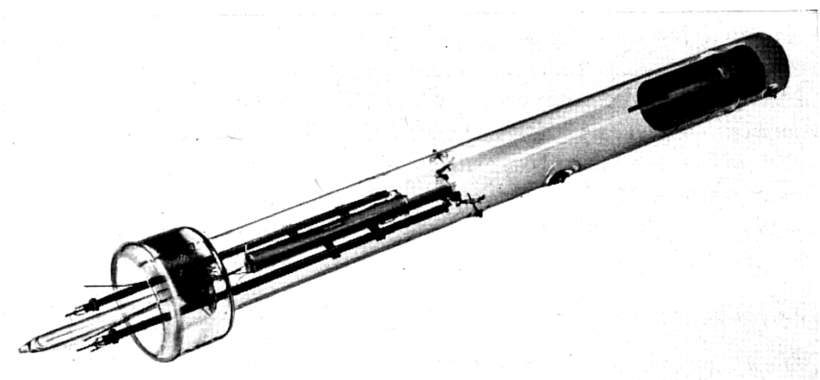

Fig. 1 — Photograph of broadband oscilloscope tube — Model III.

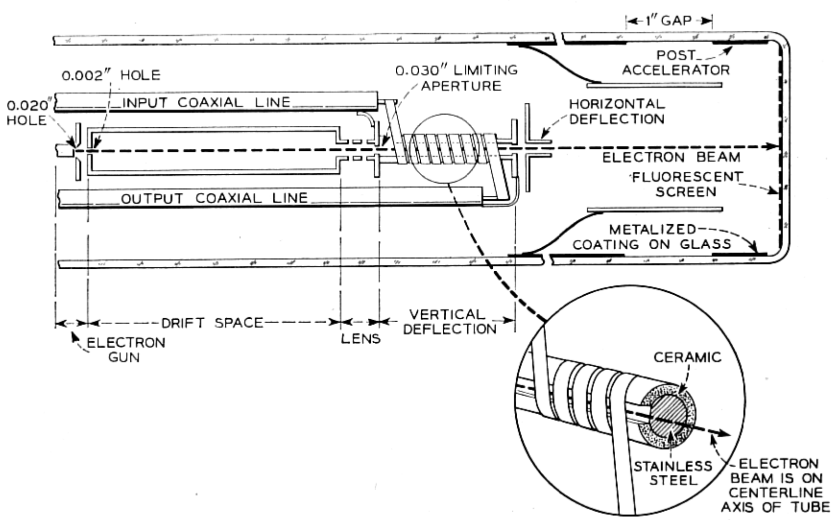

Fig. 2 — Cross section of broadband oscilloscope tube — Model III.

response from 0 to 600 mc and is useful for viewing repetitive pulses within this bandwidth. This limit is determined by the particular transition from the 76-ohm coaxial input line to the slow wave structure and is not inherent in the traveling wave deflection system. The viewing field is approximately one inch square when no post acceleration is applied. This increase in picture size is obtained by increasing the tube length and therefore the optical system of Pierce's previous model has been eliminated. With a beam voltage of 1,000 volts the sensitivity is 0.02 trace widths per millivolt which tells us that 0.41 milliwatts of power into the 76-ohm input lead is required for a peak-to-peak deflection of 10 trace widths.

II. GENERAL DESCRIPTION OF THE TUBE

The broadband oscilloscope tube of Fig. 1 consists of an electron gun which forms a small beam (0.002″ diameter) that is focused on the screen by the lens which precedes the slow wave structure as illustrated in Fig. 2. The electron gun employes a type "B" Philips impregnated cathode 0.025″ in diameter and it is capable of giving current densities in excess of one ampere per square centimeter. The gun design is simple in that we aperture the beam with a small anode hole rather than making use of a sharp crossover. The ion bombardment of the cathode was considerably reduced by aperturing the beam with a 0.020″ hole in a low voltage electrode near the cathode surface. This electrode also serves as a current control which is very useful for blanking the return trace. The 0.030″ aperture at the input of the deflection system eliminates those electrons which do not pass near the center of the focusing lens and insures that the vertical dimension of the beam in the traveling wave deflection will be small. This system of deflection is the component which is new in this tube and it will be discussed in detail in Section III. The horizontal sweep for this tube is a pure sine wave of a frequency much lower than the repetition rate of the incoming pulses. Since a single frequency is involved, the horizontal sweep circuit can be resonant. Therefore, large sweep voltages are easy to obtain. Two parallel plates $\frac{1}{4}$″ long spaced 0.060″ apart are used for the horizontal deflection system. The picture size increases with distance beyond the deflection circuit and as a compromise between over-all tube length and picture size, a drift distance of 8″ was chosen. There is a simple post acceleration lens near the screen for the purpose of increasing the intensity. Since it is a converging lens it has the disadvantage of decreasing the picture size, as a result the accelerating voltage is limited to about 3,500 volts.

The use of a strong post-acceleration lens wherein the beam actually crosses the axis before reaching the screen has been suggested by a number of people as a method of avoiding the reduction in picture size with increasing screen voltage. Such a system has been built (described in Section VI) which operated at a post-accelerating voltage of 10 kv. However, the system does suffer from increased astigmatism and more work is required before it can be used.

III. VERTICAL DEFLECTION

The vertical deflection system is a coaxial tape helix made of gold-plated molybdenum tape 0.115″ wide wound at eight turns per inch over a stainless steel arbor as shown in the enlarged sketch of Fig. 2. The rectangular opening for the beam is 0.044″ high and 0.108″ wide. At either end there is a simple transition from the 76-ohm coaxial line to the helix as shown. We see that the coaxial line is essentially turned inside out with the outer coaxial conductor becoming the inner portion of the deflecting system. This transition from coaxial line to the deflecting system represents a discontinuity which is mainly due to a radical change in geometry in a short distance. This is true even though impedance is preserved. At about 650 mc the input and output transitions are spaced about a half wavelength apart and, consequently, a large reflection occurs. Actual measurements on the tube show that the reflections from this tube are 25 db down from 0 to 600 mc (VSWR < 1.13). The bandwidth could be increased by an improved coaxial to circuit transition. The high frequency limit to this helix as a propagating structure will occur when the circumference becomes equal to one-half wavelength. At this point the discontinuities due to the slot in the ceramic spacer are one-half wavelength apart and a stop band in the propagation characteristic will appear. This will occur at about 3,000 mc for the dimensions of this tube.

The maximum angle of deflection is limited by the ratio of the length to vertical separation of tape helix and the center conductor. This angle is 3.7°.

When the beam voltage is properly adjusted, the wave and the beam travel along together and transit time effects are minimized. If the beam velocity differs from the synchronous value, the amplitude of a sinusoidal deflection will be reduced by[6]

$$\frac{\sin \dfrac{\omega l}{2}\left(\dfrac{l}{v_s} - \dfrac{l}{v}\right)}{\dfrac{\omega l}{2}\left(\dfrac{l}{v_s} - \dfrac{l}{v}\right)}, \tag{1}$$

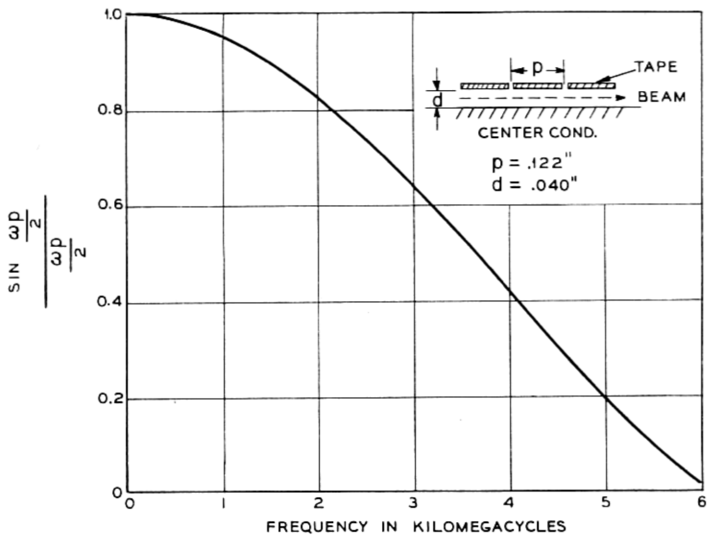

Fig. 3 — Transit time versus frequency for a beam in the presence of parallel plates.

where ω is the radian frequency, l is the length of the deflecting system and v_s and v are, respectively, the synchronous and the actual beam velocity. Equation (1) shows that, in any case, this deflection system gives better response than would a system using parallel plates. For parallel plates the reduction due to transit time effects is

$$\frac{\sin \dfrac{\omega l}{2v}}{\dfrac{\omega l}{2v}}, \tag{2}$$

where the symbols have the meanings given above.

There is another point to consider and that is the transit time effects due to the finite width of tape. Fig. 3 shows the magnitude of this effect. Sinusoidal signals suffer only a loss in amplitude because of transit time effects; however, any other waveform will be distorted. This can best be seen by considering what happens when a square wave with a zero rise time amplitude V_m is applied to this deflecting system.

The vertical deflection on the fluorescent screen will be proportional to the transverse velocity gained by the beam in passing through the deflecting system. This is given by

$$v_y = \frac{e}{m} \int_0^t \frac{V}{d}\, dt. \tag{3}$$

When the voltage goes from zero to V_{max}, some electrons will just be entering under a tape. These electrons will be influenced by V_{max} for all the time that they are under the tape. Electrons which have further progressed under the tape will be influenced for a lesser period of time. When the proper limits of integration are placed on (3), it reads

$$\begin{aligned} v_y &= \frac{e}{md}\int_0^{x/u_0} V_m dt, \\ &= \frac{e}{md} V_m \left(\frac{x}{u_0}\right) \quad 0 \leqq x \leqq p, \\ &= \frac{e}{md} V_m \tau \quad p \leqq x, \end{aligned} \tag{4}$$

where p is the pitch of the tape helix and τ is the time taken by the beam in traveling a distance of $p \left(\tau = \frac{p}{u_0}\right)$. Equation (4) shows that a square wave with a zero rise time will appear on the screen to have a rise time τ. For the dimensions of this tube τ is 1.65×10^{-10} seconds.

IV. SPOT SIZE AND SENSITIVITY

The elements in this tube which determine spot size are the 0.002″ hole and the subsequent lens system. This hole is imaged on the fluorescent screen and its size at the screen is determined primarily by the intervening lens system. Theoretically the spot size should be 0.007″- however, in most cases the measured size was approximately 0.010″; Part of this difference is due to the fact that the beam boundaries are not clearly defined, consequently measurements may be somewhat inaccurate.

Sensitivity is best expressed as trace width of deflection per volt of applied signal. This is particularly significant since the amount of information which can be obtained from a picture depends not on the absolute height of the picture but rather on the number of elements (trace widths) which make up the picture. Thus it is desirable to have the spot size as small as possible. The vertical sensitivity of this tube is 50 millivolts per trace width and the field is about 100 trace widths both horizontally and vertically. A 25 milliwatt sinusoidal signal will give maximum vertical deflection. The horizontal sensitivity is 0.42 volts per trace width or 42 volts per inch.

V. WRITING SPEED

One of the most important considerations in high speed oscilloscopes is the writing speed of the instrument. This factor tells how fast the sweep can travel and still give recordable information. This is usually expressed in trace widths per second. To measure the writing speed of the broad-band oscilloscope a square wave with a 50 millimicrosecond rise time was applied to the tube and the repetition rate of the square wave was lowered until the rise time portion could no longer be observed. With 2000 volts of post acceleration and a square wave with a height of 100 trace widths, rise time was still visible at a repetition rate of 50 times a second. This means that the writing speed was 2×10^9 trace widths per second when repeated 50 times a second. To compare this with the conventional method of stating writing speeds, the number of "frames" instrumental in forming an image must be known. For a human, the persistence of vision is approximately $\frac{1}{20}$ second. This means that the number of events occuring in this period aid in forming an image; any greater number is superfluous. Using the above numbers, our writing speed becomes 0.8×10^9 trace widths per second. This would also be the maximum writing speed detectable on film with the same sensitivity as the human eye. The writing speed of this tube should be compared to that of 1×10^{11} trace widths per second available in special high speed oscilloscopes. The relatively low writing speed of this tube makes it more useful in observing recurrent phenomena rather than transients (or single pulses). The most effective way of obtaining a greater writing speed is to increase the beam voltage. This results in a beam with a greater power density since not only do the electrons strike the screen with a greater velocity, but also the current density in the beam may be increased. However, as previously mentioned, this results in a loss in sensitivity. This can be overcome to some extent by using a strong post acceleration lens and high voltages.

VI. ALTERNATE LENS SYSTEM FOR POST ACCELERATION

In order to obtain higher writing speed in the broadband oscilloscope tube, a cross-over lens was built to compare this type of system with "ordinary" post acceleration. An operating voltage of 10,000 was chosen. A photograph and cross-section of the tube is shown in Figs. 4 and 5. The lens consists of two cylinders whose diameters are in the ratio of 1.5 to 1. The small cylinder must be long enough to prevent fields from the lens from penetrating into the horizontal deflection region. This essentially determined the position of the lens center. The diameter of the small cylinder was determined by setting a limit to the amount of aberration which can be tolerated. It was decided that the small cylinder diameter should be three times the maximum deflection at the lens center. The beam with its increased velocity travels about ten inches before it strikes the fluorescent screen.

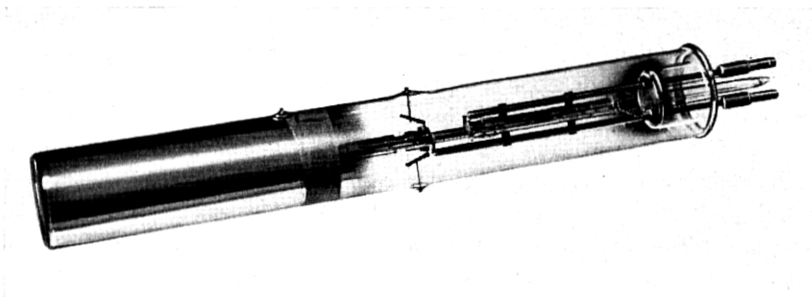

Fig. 4 — Photograph of broadband oscilloscope tube — Model IV.

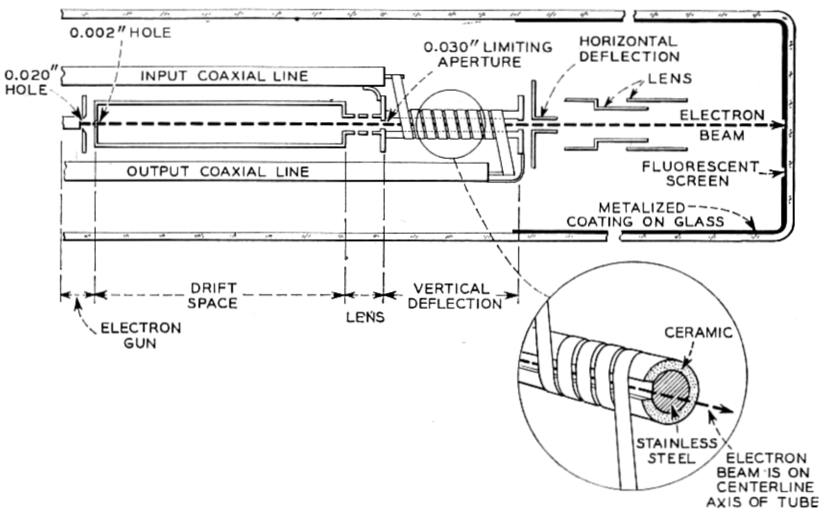

Fig. 5 — Cross section of broadband oscilloscope tube — Model IV.

For this simple lens system illustrated in Fig. 6 the image distance is fixed by the distance from the lens center to the screen. However, the object distance as defined by distance between the lens center and the center of deflection is different for vertical and horizontal deflections. This results from the axial displacement of the deflection regions and causes a difference in the magnification of the horizontal deflection system as compared to the vertical. With the use of Spangenberg's[7] P-Q curves one can find the crossover point (2) for each value of V_2/V_1. This allows us to calculate the magnification and the results are plotted in Fig. 7, together with the observed magnification. The agreement is fairly good until high values of V_2/V_1 are reached — here the observed curve seems to "saturate".

This effect was corrected and the brightness was improved by using an "aluminized" screen. The screen is made by evaporating a thin (approx. 5000 Å) film of aluminum on the back of the phosphor.[8] This is necessary since at high velocities the electrons penetrate so deeply into the phosphor that secondaries do not readily escape; consequently the screen charges to a potential lower than that applied to the lens and the beam is slowed down at the screen. A further advantage of aluminizing is the fact that the aluminum film acts as a mirror and reflects forward part of the light that was originally lost at the back of the screen. Fig. 8 shows the magnification of an aluminized tube as a function of the lens voltages. The "astigmatism" of this particular design is worse than the conventional "post acceleration" systems and more effort is needed to improve this feature.

VII. MECHANICAL DESIGN

The mechanical design of the broadband oscilloscope tube is similar to the design of a conventional cathode ray tube. That is, the various electrodes which make up the tube are mounted in cylinders which are supported from ceramic rods. The materials used in the tube are type 302 and 304 stainless steel, 326 Monel and molybdenum. The type of glass used is 7052 Pyrex. The conductive coating inside the envelope is tin oxide. The screen is a blue sulphide phosphor, seven to ten microns particle size.

In constructing the tube, the various sub-assemblies consisting of the gun, focusing lens and RF structure are properly aligned and mounted as a unit from the coaxial lines. Before the tube is sealed in its envelope, the RF match of the helix circuit is measured. When the electrical

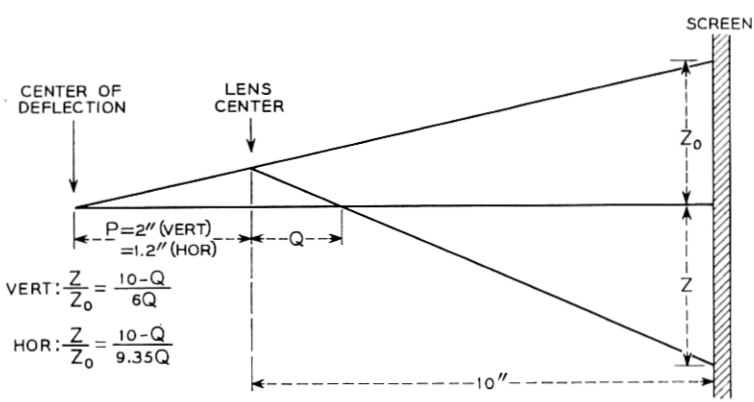

Fig. 6 — Method for determining magnification.

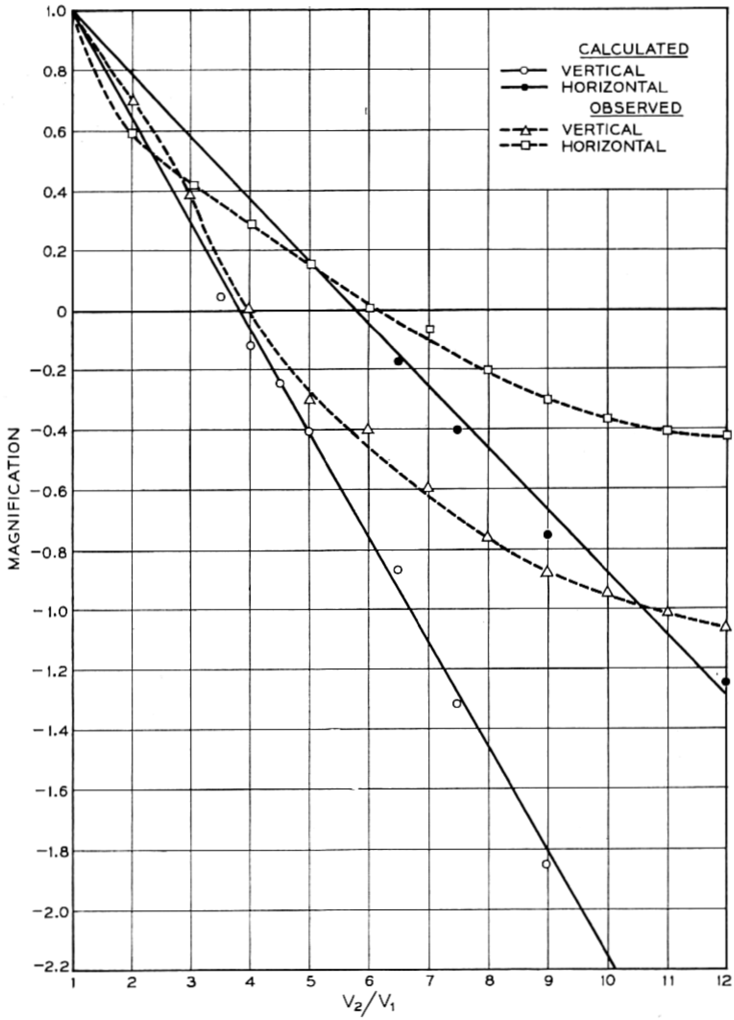

Fig. 7 — Magnification versus V_2/V_1, for cross-over lens with non-aluminized screen.

tests have been completed, the alignment of the entire structure is checked using an optical comparator. The alignment of the drift tube, focusing electrodes and RF structure is acceptable when the axial deviation is less than one part in five thousand. The cathode assembly must be within three thousandths of an inch axially.

Although the alignment of the electrodes for the broadband oscilloscope tube appears to be rigid, it is not a difficult tube to build.

VIII. APPLICATIONS

Currently, studies are being made on microwave regenerative repeaters with pulse repetition rates of one hundred and sixty million pulses per second. Timing pulses needed for this system are only 2 millimicroseconds wide at the base. Bandwidths of 500 megacycles or more are required for satisfactory reproduction of these short pulses.

Fig. 9 is an enlarged photograph of timing pulses occurring at the

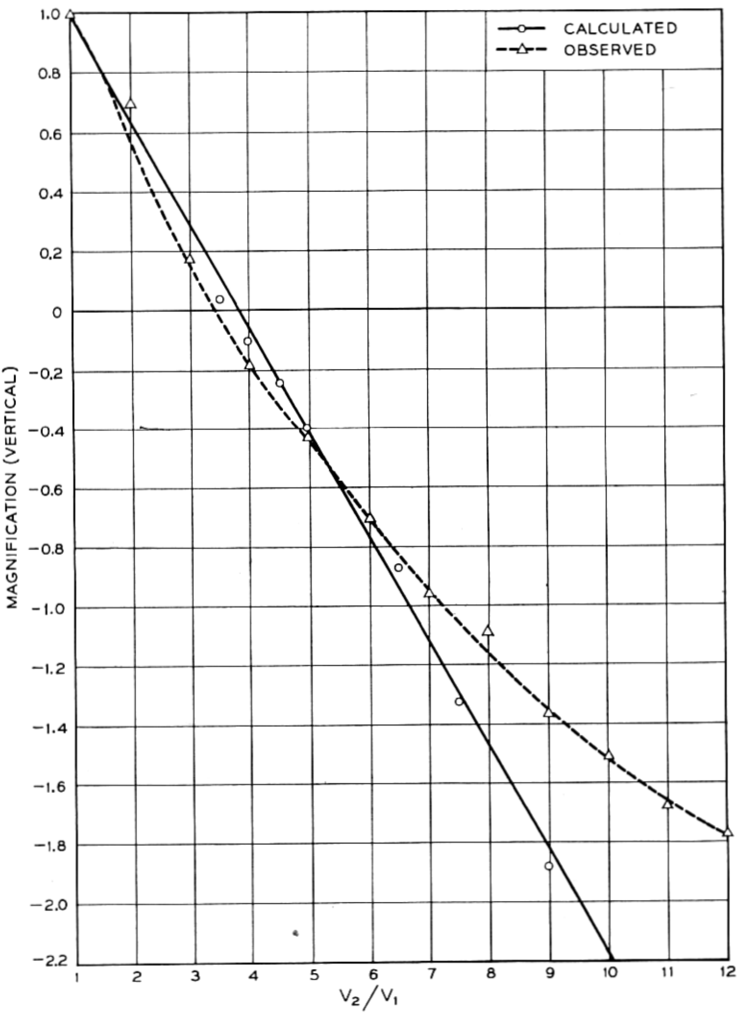

Fig. 8 — Magnification versus V_2/V_1, for cross-over lens with aluminized screen.

rate of one hundred and sixty million pulses per second as seen on the face of the broadband oscilloscope tube. It will be noted that the slight imperfections in the wave caused by leakage of pulses at half this rate can be clearly seen. Sine wave frequencies considerably higher than 160 megacycles have been observed on the broadband oscilloscope tube. Fig. 10 shows an enlarged photograph of an 800 megacycle sine wave as seen on the face of the broadband oscilloscope tube.

By using television techniques and televising the image on the face of the broadband oscilloscope tube, a much larger image can be displayed on a television monitor. The waveform on such a monitor is enlarged by a factor of 10, with an over-all vertical deflection sensitivity of one volt per inch. The picture size compares favorably with the size of trace one normally views on a 5″ cathode ray tube. Successful operation of a system of this type requires that the image be a steadily recurring display. In this application the broadband oscilloscope tube might be regarded as a storage device where information is written in at the rate of ten million pulses per second and read out by television scanning at a 60 cycle rate.

Fig. 11 shows a typical photographic reproduction of the face of the television monitor picture tube. Fig. 11(a) is the detected envelope of an 11 kmc pulse group at the output of the microwave modulator. Fig.

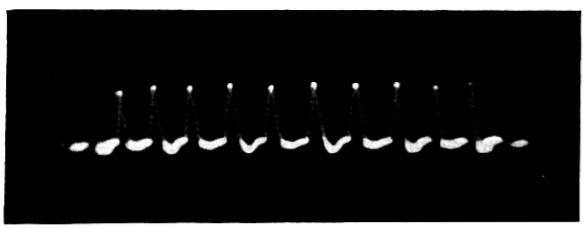

Fig. 9 — Photograph of timing pulses.

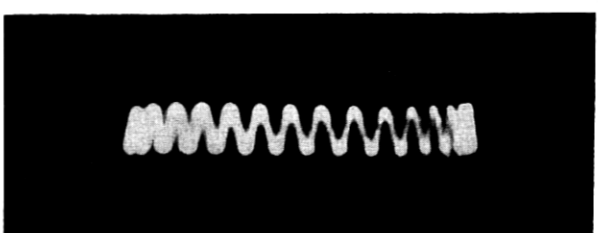

Fig. 10 — Photograph of 800 mc sine wave.

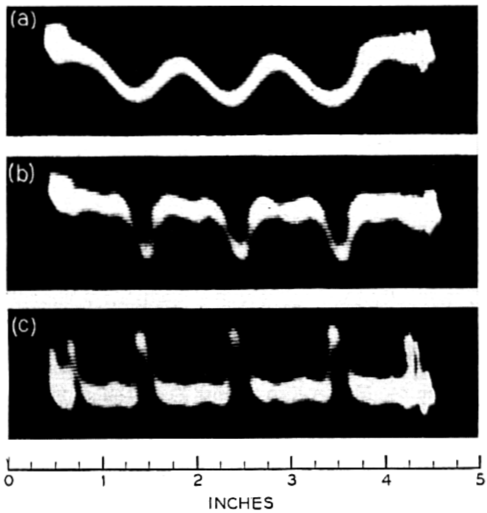

Fig. 11 — Photograph of pulses on the television monitor.

11(b) is the detected envelope of the same pulse group after it has been retimed in an 11 kmc microwave gate by the 2 millimicrosecond baseband timing pulses shown in Fig. 11(c).

IX. CONCLUSION

The broadband oscilloscope tube with its inherent bandwidth has made it possible to pursue studies on systems using millimicrosecond pulses. The present writing speed of this tube restricts its use to high speed repetitive pulses. The writing speed could be increased without a reduction in deflection sensitivity by increasing the cathode current density. The bandwidth could be increased with an improved transition from the coaxial line to the vertical deflection system. In principle the bandwidth could be extended to 2500 megacycles without appreciable loss in sensitivity.

A combined unit employing both the oscilloscope tube and the television system results in a broadband oscilloscope which is capable of resolving one millimicrosecond pulses. The reproduced enlarged images compare favorably in size with presentations on a conventional 5″ oscilloscope tube. The availability of the unit greatly facilitates progress towards a short pulse microwave regenerative repeater which would be capable of transmitting more than 100 million pulses per second.

X. ACKNOWLEDGEMENTS

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