mittance may be in error more than this, especially in the case of the closely spaced tubes.

Despite many precautions in the design of the cavity, considerable trouble was experienced with higher-order waves distorting the principal wave in the measurement zone. Some of this was eliminated by redesign of tube contacts; but in other instances, where the trouble originated within the tube from such things as a tilted or eccentric cathode, nothing could be done but reject that tube for testing purposes.

Acknowledgment

The writer wishes to acknowledge the contributions of S. Ramo and J. R. Whinnery to the theoretical analysis of the problem, and of J. E. Beggs for the many sample tubes which were used.

The Cyclophon: A Multipurpose Electronic Commutator Tube*

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Summary—**Electronic switching or commutation provides an inertialess mechanism for precise high-speed operation, and permits a multiplicity of circuits to be controlled by relatively small voltages such as are encountered in radio reception. The Cyclophon tube is one particular form of electronic switch which provides for the control of twenty-five separate circuits. This control is so precise that it can be used as a modulator and demodulator for pulse-time-modulation transmission and reception. Some further applications are in the fields of telemetering, pulse generation, phasing, frequency multiplication, counting of electric impulses, monitoring, and synchronizing-wave-form generation in television.**

THE NAME "Cyclophon" is given to a generic type of tube utilizing a beam of electrons as a switching or commutating element. The application of an inertialess switching device of this nature to a variety of problems has been long recognized and many references to it can be found in the literature.

As far back as 1906, Diekmann and Glage applied for a patent on a cathode-ray relay which was claimed to be capable of performance substantially equivalent to that achieved with a metallic switch.[1] More recently, radial types of commutating tubes have been described which are applicable to signaling and control systems.[2]

The Cyclophon may take a variety of forms utilizing various types of construction and methods of control. These include the cathode-ray-oscilloscope type, the aforementioned radial type, forms involving linear construction, or a combination of any of these. The electron beam may consist of a fine beam of electrons or, alternatively, a flat sheet capable of large current capacity. Control of the beam may also be accomplished in a variety of fashions including both electric and magnetic means. Whatever the form utilized, however, the functional characteristics are similar, in that results equivalent to those obtained with a moving metallic contactor are achieved.

I. Theory of Operation

A. General Description

The component parts of a typical Cyclophon tube are shown schematically in Fig. 1. The portions labeled

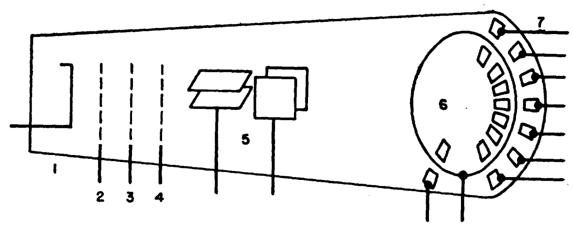

Fig. 1—Schematic representation of a Cyclophon tube, consisting of (1) cathode, (2) control grid, (3) electrostatic focusing element, (4) accelerating anode, (5) electric-field deflection system, (6) aperture plate, and (7) collector or secondary-emitting elements.

1 to 4 comprise a cathode-ray gun consisting of a cathode (1), control grid (2), electrostatic focusing element (3), accelerating anode (4), and electric-field deflection system (5). This gun produces a sharply defined beam of electrons, which may be deflected in any direction by impressing proper voltages on the deflection plates. Thus, in the tube illustrated, the beam is caused to describe a circular path in the plane of the target. Other types of deflection paths, and deflection and focusing systems, may of course be utilized.[3]

The gun structure is followed by a "stopper" or aperture plate, containing as many apertures as there are channels or circuits to be controlled. A series of targets (7), which may be current collectors or secondary-emitting dynodes, are placed directly behind the aperture-plate openings.

B. Secondary Emission

The current output of each channel may be increased several times by the use of secondary emission from the

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† Federal Telecommunication Laboratories, Inc., New York, N. Y.

[1] M. Diekmann and G. Glage, "Continuously quantitatively acting relay employing the electrical deflecting power of cathode rays," D.R.P. No. 184710, Klasse 21g, Gruppe 4, application date, Oct. 10, 1906, publication date, April 7, 1907.

[2] A. M. Skellet, "The magnetically focused radial beam vacuum tube," *Bell Sys. Tech. Jour.*, vol. 23, pp. 190–202; April, 1944.

[3] O. S. Puckle, "Time Bases," John Wiley and Sons, Inc., New York, N. Y., 1943; p. 9.

target anodes (dynodes). To obtain such a secondary current flow, the aperture plate is maintained at a higher positive potential than the dynodes. The dynode current then is a function of primary beam current, secondary-emission ratio, and aperture-plate-to-dynode voltage.

C. Dynode Characteristics and Equivalent Circuits

A typical dynode volt-ampere characteristic is shown in Fig. 2 for several values of primary beam current.

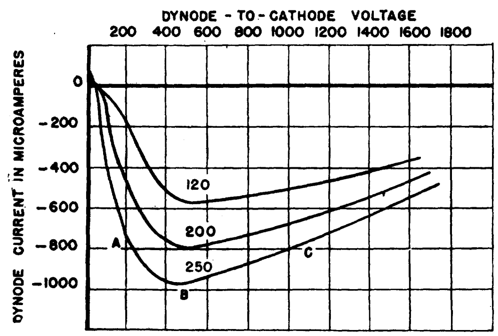

Fig. 2—Dynode volt-ampere characteristic for the three indicated values of primary beam current in microamperes.

The forms of these curves suggest three modes of operation and equivalent circuits. If the operation is such that the quiescent operating point is at A and assuming an output voltage which is small compared to the dynode voltage, the equivalent circuit may be represented by a current generator whose current is equal to $(N-1)i_pf(t)$, a switch or commutator, each contact having a negative resistance $-R$ and a load impedance Z. Such an equivalent circuit is shown in Fig. 3. The switching function $f(t)$ is derived from the geometric configuration of the apertures and from the type of cyclic variation of the sweep used. The internal contact resistance corresponds to the slope of the dynode characteristic at the operating point. Analysis then shows that the output-voltage function e_0 (i.e., the voltage appearing across the load impedance Z) may be written as

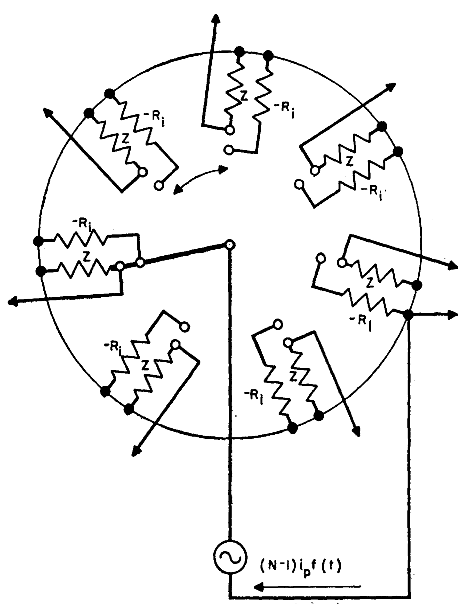

Fig. 3—Equivalent circuit of the Cyclophon tube. The tube may be represented by a rotating switch having a contact resistance $-R$.

$$e_0 = \frac{(N-1)i_pf(t)ZR}{(Z-R)}. \tag{1}$$

This equation shows that, with the described mode of operation, the output voltage may become exceedingly large if Z is a positive resistance[4] and almost equal or equal to R. Since for normal operation it is stipulated that the output voltage is small with respect to the dynode voltage, linear conditions prevail. Examination of the curves of Fig. 2 shows that a large increase in dynode voltage will bring the internal resistance into a positive region, thus causing the output voltage to reach equilibrium. This effect of secondary emission may be regarded as regenerative and thus must be carefully considered when using reactive loads. Under these conditions, where the output dynode voltage is large, nonlinear operation results and the equations indicated hold only for operation over the limited linear portion of the curves.

If the quiescent operating point is at C, Fig. 2, the equivalent circuit is similar to that described above, with the contact resistance replaced by a positive resistance. Thus the output voltage may be written as

$$e_0 = \frac{(N-1)i_pf(t)ZR}{R+Z}. \tag{2}$$

However, if the operating point is at B, the internal contact resistance is much greater than any normal load impedance, so that the load current becomes substantially independent of the load impedance. Hence, the output voltage becomes

$$e_0 = (N-1)i_pf(t)Z. \tag{3}$$

The above equations are useful in the analysis of the operation of Cyclophon tubes utilizing secondary emission. It should be noted that Z is in the form of a differential operator, since $f(t)$ may not necessarily be a simple sinusoidal function. Of course, the tube operation may be suitably analyzed by the usual graphical method using the characteristic curves.[5] These analyses are simplified if the load is a pure resistnace.

D. Cross Talk

An important characteristic of any type of commutating tube is cross talk, the interference obtained in one channel when a signal appears in another channel. It is obvious that the dynode circuits most affected are those which are physically adjacent in the tube.

Cross talk may be encountered for several reasons. Circuits in physical proximity may affect each other by either magnetic or electric induction. Thus cross talk

[4] A. W. Hull, "The dynatron, a vacuum tube possessing negative resistance," PROC. I.R.E., vol. 6, pp. 5–36; February, 1918.

[5] A Preisman, "Graphical Construction for Vacuum Tube Circuits," McGraw-Hill Book Co., Inc., New York, N. Y., 1943; p. 130.

may originate in the Cyclophon by electric induction through the capacitance between dynodes or dynode leads. Two dynode circuits are shown schematically with their interdynode capacitances and resistance loads in Fig. 4.

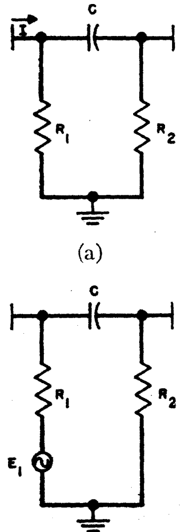

Fig. 4—Dynode circuits, including source of voltage or current and interdynode capacitances.

Assume that a sinusoidal current I flows as shown in Fig. 4(a). Then the voltage across R_1 is

$$E_1 = \frac{IR_1(jX_c + R_2)}{R_1 + jX_c + R_2}, \tag{4}$$

and the voltage across R_2 is

$$E_2 = \frac{IR_2R_1}{R_1 + jX_c + R_2}. \tag{5}$$

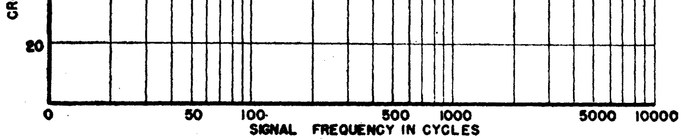

Fig. 5—Curves of cross talk as a function of signal frequency for the several specified values of load resistance (ohms). The cross talk indicated is caused by the interdynode capacitance of 2 micromicrofarads.

The cross-talk ratio is usually expressed in decibels, so that:

$$\text{db cross talk} = 20 \log_{10} \frac{(jX_c + R_2)}{R_2}. \tag{6}$$

An alternate condition arises when a signal is impressed in the dynode circuit as shown in Fig. 4(b). For this case the cross talk is similarly derived as

$$\text{db cross talk} = 20 \log_{10} \frac{R_1 + R_2 + jX_c}{R_2}. \tag{7}$$

Curves of cross talk as a function of frequency for several values of load resistance and assuming a total interdynode capacitance of 2 micromicrofarads are shown in Fig. 5.

Cross talk may also arise if more than one dynode is switched at one time. To minimize this effect, the electron beam must have a sharply defined boundary and must have a diameter consistent with the operational requirements.

II. Construction

The design considerations, construction, and processing vary only in detail for different types of tubes, and hence the following description is confined to one typical design of Cyclophon, designated as the Type X153C.

In the construction of the Cyclophon, four main objectives had to be realized, namely, maximum output, minimum interchannel cross talk, uniformity, and long life.

Preceding the construction of actual tubes, tests were conducted on models in an electrolytic tank and rubber-membrane apparatus to determine the optimum relations between various elements which would insure minimum cross talk and stable operation. These tests were also supplemented by experiments with tubes built in a demountable fashion.

The high secondary-to-primary-emission ratio and the uniformity desired required considerable experimentation before satisfactory results were achieved. It must be realized that, with 25 dynodes in one tube, one inoperable or low-output dynode will considerably decrease the usefulness of the tube. A reliable material capable of uniform secondary-emission yield must be used. Beryllium copper was chosen, although other alloys may be employed.

The target end of the cyclophon is a single assembly consisting of a metallic disk (aperture plate) with 25 accurately and uniformly spaced sectoral apertures and shields arranged in a circle. The 25 dynodes and support wires are assembled to two eyeleted mica disks and a 26-lead stem. When the aperture plate is assembled to the dynode assembly, each dynode is automatically aligned behind each aperture. The dynode is slightly larger than the corresponding aperture. The various components are shown in Fig. 6.

The dynodes undergo special processing before the aperture plate is attached. The active faces are carefully surfaced and degassed, and the dynodes are then oxidized. The entire dynode assembly receives identical treatment; thus great uniformity exists among the dynodes of any one structure. While the tube is on final exhaust the dynodes are bombarded, producing a higher and more uniform secondary-emission yield.

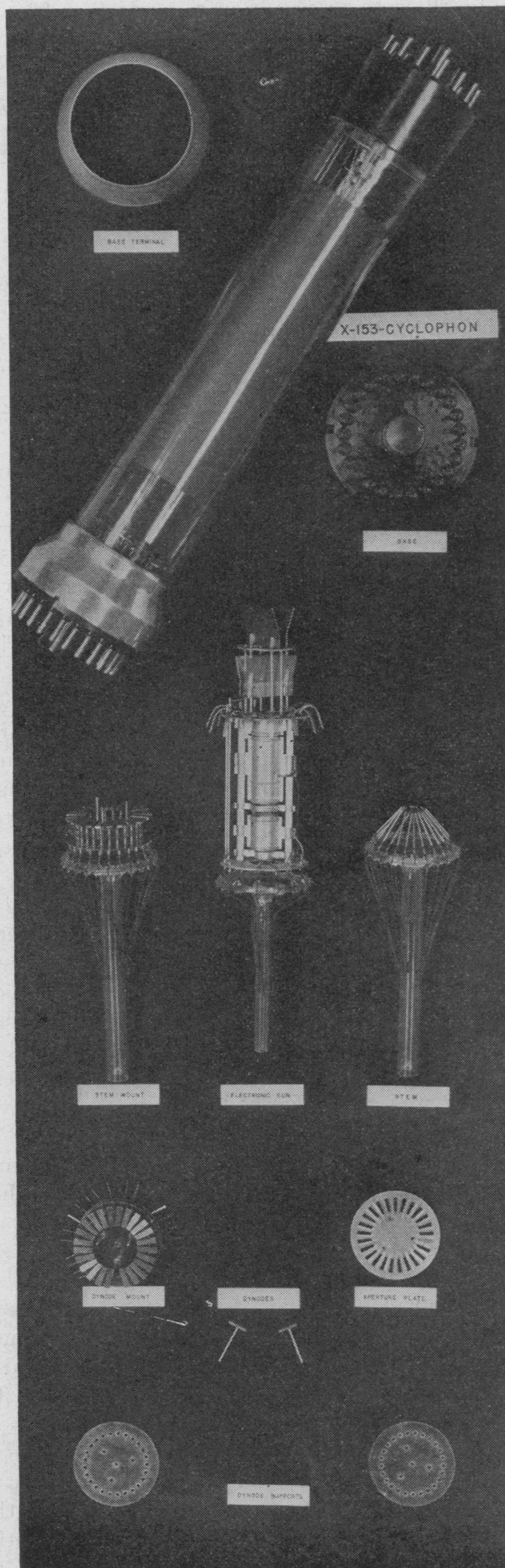

Fig. 6—The various components of a Cyclophon tube, illustrating its form of assembly.

The shortness of the target assembly and the large number of lead wires supporting it produces an extremely rugged structure. Life tests indicate that the cathode emission fails before any decrease in secondary-emission yield manifests itself, and it may be concluded that tube life is dependent only on the cathode.

Table I gives the operating characteristics of two types of Cyclophon tubes which have been manufactured. The X153C is a low-current, high-impedance type, while the X153G can operate with approximately 30 times the current and a corresponding reduction of dynode-aperture impedance. Fig. 7 illustrates representative type of Cyclophon tubes.

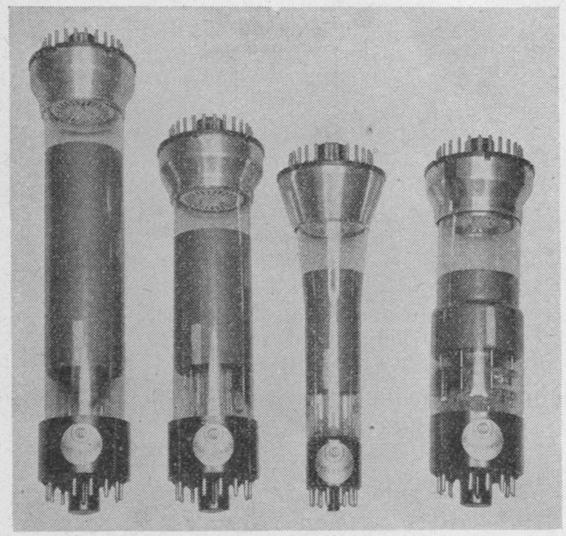

Fig. 7—A group of representative Cyclophon tubes. The three tubes on the left are high-impedance tubes, whereas the tube on the right is capable of supplying a dynode current of 30 milliamperes.

III. Application

The characteristics of Cyclophon tubes are such that a variety of applications is possible. These applications cover a range of subjects, including switching, separation and demodulation for systems of communication, telemetering, generation of pulse wave forms, phasing, frequency multiplication, and counting, to mention a few.

A. Switching

The limitations of mechanical switching are those of speed, accuracy, and mechanical wear. The Cyclophon tube, being an electronic device, finds application where either high speed, accuracy, or both characteristics, without variation because of inertia or wear, are necessary. The limitation of speed of operation of the Cyclophon is of the order of megacycles per second, and for normal speeds of operation the limitation is not in the tube itself but in the type of output circuits used. The fundamental accuracy is a function of the inherent rsistance noise, which is made up of a combination of the shot effect, secondary-emission noise, and thermal-agitation noise. Measurements have indicated that the total noise power is of the same order as that of a pentode amplifier, and these limitations can therefore be determined in the same manner as for this type of device. For some applications, of course, the accuracy is determined not by the noise power but by variation of physical dimensions with temperature, changes in beam cross section due to external fields, and fluctuating supply voltages. These variations can be reduced to an acceptable value by control of the external parameters of operation, however. Two basic types of switching can be distinguished: low-impedance switching and high-impedance switching. The Cyclophon tubes of the X153C type are essentially high-impedance devices, and to obtain extremely low impedances auxiliary tubes must be used. For example, thyratron tubes can be controlled by the output of the Cyclophon and this latter tube used only to switch from one thyratron to the next. In this manner the internal impedance of the X153C, which is of the order of thousands of ohms, can be effectively reduced to that determined by the controlled tube, which may be a few hundred ohms or less.

TABLE I

CYCLOPHON CHARACTERISTICS

Heater	X153C	X153G	
Voltage (alternating or direct)	6.3	6.3	
Current (amperes)	0.6	1.5	
Interelectrode capacitances			
Dynode to dynode (micromicrofarads), approximate	2.0	2.0	
Dynode to aperture plate (micromicrofarads), approximate	2.0	2.0	
Focusing	Electrostatic	Electrostatic	
Deflection	Electric field	Electromagnetic	
Over-all length (inches)	12 11/16	7½	
Diameter of bulb (inches)	2	2¼	
Mounting position	Any	Any	
Gun base	Medium shell Diheptal 12-pin	Medium shell Diheptal 12-pin	
Target base	Special 26-pin	Special 26-pin	
Number of dynodes	25	25	
Type of sweep	Circular	Circular	
Typical Operation:			
Accelerating anode volts	2000	2000	1000
Focusing anode volts, approximate	200	—	—
Focusing cup No. 1 volts	—	+10	+10
Focusing cup No. 2 volts	—	−90	−90
Aperture anode volts	2000	2000	1000
Dynode volts	500	500	500
Deflection factor	135–170 (volts per inch)	70 (gauss per inch)	50
Dynode current (milliamperes)	1	30	12
Dynode load resistance (ohms)	50,000	1000	5000

Fig. 8(a) illustrates the use of the Cyclophon tube in a switching circuit. The tube voltages are those for normal operation. The signal source to be commutated is applied to the aperture plate through impedance Z and the signals are obtained from the dynode outputs labeled 1, 2, n. The speed of commutation is determined by the source applied to the deflection plates. Of course, in the example shown the source must be arranged so that two quadrature voltages are obtained to cause the beam to rotate across the apertures.

With this switching arrangement, two types of operating characteristics can be obtained: a variable-resistance characteristic, or one possessing a constant resistance. The former characteristic is obtained by operating the Cyclophon tube over the range OCD indicated by Fig. 8(b), which shows the aperture-dynode

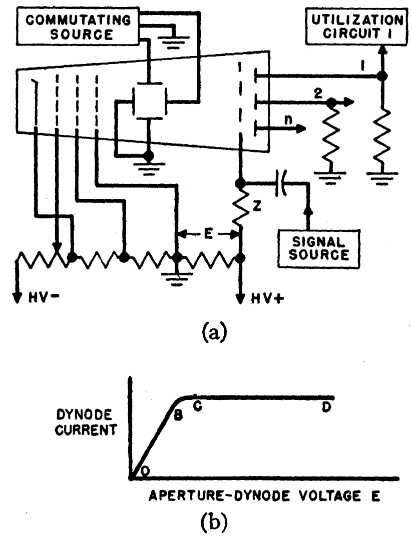

Fig. 8—(a) Switching circuit: The signal to be switched is applied to the aperture plate while the output signal is obtained at the dynodes 1, 2, n. (b) Cyclophon transfer characteristics. A constant-impedance characteristic is obtained by operation over the region OB. Variable impedance is obtained by extending operation to include CD.

transfer characteristic, while linear operation is achieved by limiting the tube swing to the region OB. By proportioning the voltage E, the proper quiescent conditions can be obtained for either type of operation.

Since switching covers a large range of functions, only a few such applications need be mentioned. These properties have been used for telemetering purposes and switching between various instruments at a rapid rate. Other applications have been in telephone circuits for accomplishing several of the functions previously obtained with mechanical switching.

B. Pulse-Time Modulation

An important use of the Cyclophon is found in its application to voice multiplexing by means of pulse-time modulation.[6] In fact, the term Cyclophon is derived from the Greek form "kyklos" (circle) and "phone" (speech), or "speech in a circular sequence," denoting the original multiplex application for which the tube was constructed. The Cyclophon is utilized both in the modulator unit for generating the required pulse series and also in the demodulator which separates the various channels and translates the time-modulation displacement into the normal voice currents.[7]

[6] E. M. Deloraine and E. Labin, "Pulse time modulation," *Elec. Commun.*, vol. 22, pp. 91–98; February, 1944.

[7] D. D. Grieg and A. M. Levine, "Pulse-time-modulated multiplex radio relay system-terminal equipment," *Elec. Commun.*, vol. 23, pp. 159–178; June, 1946.

In an application such as pulse-time demodulation, where use is made of the variation of output current as the beam is varied in position with respect to the aperture, the transfer characteristic is a function of the electron-beam cross section. For example, if the beam is circular, the variation in position across the aperture dynode elements will give a functional output-current variation represented by the expression (see Appendix)

$$i_d = \frac{4I}{\pi D^2}\left[\frac{D^2}{4}\sin^{-1}\frac{2(d-d^2)^{1/2}}{D} - \left(\frac{D}{2}-d\right)(dD-d^2)^{1/2}\right] \quad (8)$$

where I is the effective beam current, D is the beam diameter, and d is the displacement relative to the fixed apertures.

This expression is derived on the basis of the geometric variation of the sector area of a circular beam passing a straight-line barrier, and assumes constant beam-current density. Fig. 9 shows a plot of this function with the aperture-plate dimensions corresponding to the X153C type tube.

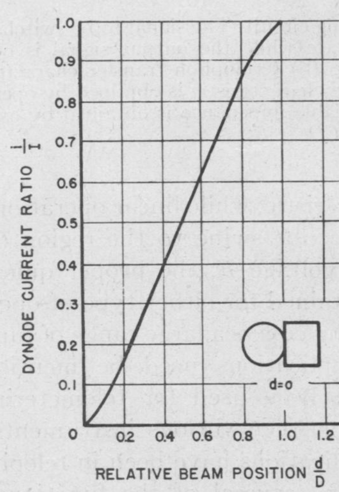

Fig. 9—Cyclophon demodulation characteristic. D=beam diameter, and I=beam current.

It should be noted that a linear function may be obtained by varying either the aperture shape, beam geometry, or the duration of the grid keying pulse.

C. Pulse Generation

By causing the beam to pass the aperture-plate openings, a pulse of current is caused to flow in the output dynode load circuits. This property can therefore be utilized for pulse generation. The build-up time of the pulse thus obtained, assuming that the impedance characteristics of the output load circuits are sufficient to pass the required band of frequencies, is given for tubes of the X153C type by the expression

$$t = \frac{D}{\pi L f_c} \quad (9)$$

where D is the beam diameter, L is the mean diameter of aperture plate, and f_c is the frequency of switching.

If the beam is of circular cross section, the build-up characteristic of the pulse is of the same shape as that shown in Fig. 9. The width of the pulse is determined by the duration of time the beam is within the aperture windows and is given by

$$w = \frac{(A+D)}{\pi L f_c}. \quad (10)$$

The decay time is similar to that of the build-up time. Since the shape of the pulse is thus a function of the frequency of commutation f_c, beam width, and aperture dimensions, a large variety of wave shapes can be obtained by manipulating these characteristics. Fig. 10 shows an oscillogram of the pulse wave forms obtained by utilizing the Cyclophon as a pulse generator. The repetition rate of the pulses thus derived is likewise a function of the frequency of commutation as well as the number of aperture dynode elements utilized.

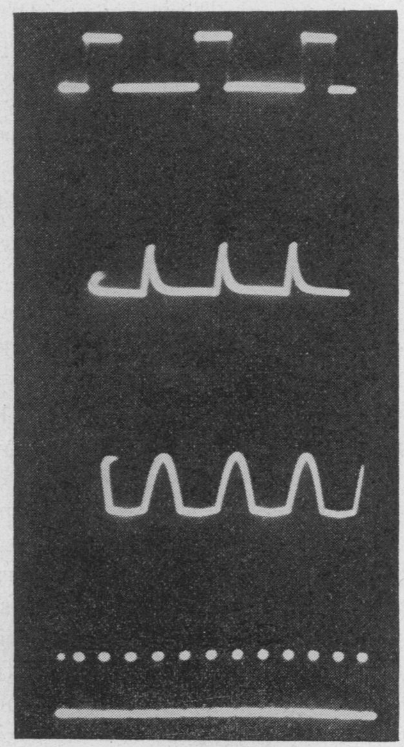

Fig. 10—Several wave forms obtained by using the Cyclophon as a pulse generator.

D. Pulse Delay and Phasing

Since the pulses derived at each aperture dynode element are generated in sequence, a division of the output pulse of the Cyclophon tube can be made in such a manner as to obtain sets of pulses with each pulse series delayed from the previous one by a given amount. This delay is dependent on the number of dynode aperture elements M, as well as the frequency of commutation, and is given by the expression

$$T = \frac{1}{M f_c}. \tag{11}$$

If, in place of pulses, phased sinusoids are required, tuned circuits responding to a single frequency may be substituted for the dynode output resistance. In this case the angle of phase delay is given by the mechanical angle between the adjacent dynode aperture elements. For example, for the X153C, the angular delay is approximately 14.4 degrees, although any multiple of this delay may be obtained by grouping the elements.

E. Frequency Multiplication

The tuned dynode circuits may, of course, be tuned to a harmonic of the pulse-repetition rate. Alternatively, all dynode elements may be connected in parallel and fed to a common load impedance which is tuned to nM times the commutation frequency, where n is the harmonic multiple chosen. Fig. 11(a) illustrates the circuit

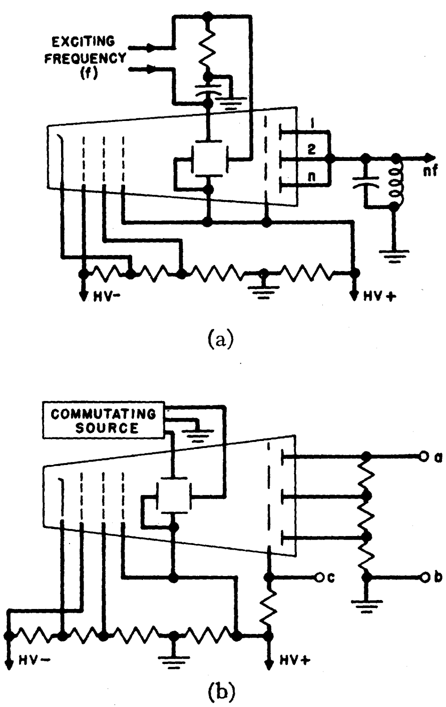

Fig. 11—(a). The Cyclophon is used as a frequency multiplier. An output corresponding to nf is obtained across the tuned circuit. (b) High-speed potentiometer. The terminals are labeled a and b with c as the common contactor.

diagram for a Cyclophon used in this manner. For each passage of the beam across the aperture dynode element a pulse of current is injected into the tuned circuit, and thus a frequency multiplication is obtained.

F. Voltage Divider

An interesting application of the Cyclophon tube is its use as a high-speed voltage divider. In this case resistances are connected to each dynode with the aperture plate serving as the common contractor. The resulting configuration may be used in the manner normal to any voltage divider. A representative circuit arrangement for this application is shown in Fig. 11(b).

In place of the resistances, other circuit elements such as inductances may be used, or a capacitance voltage divider may be constructed provided the resistance return for each dynode element is included in the circuit.

G. Miscellaneous Applications

Other applications include counting of electrical impulses, blanking for noise reduction in pulse systems, monitoring and control, and synchronizing-wave-form generation in television. These constitute only a few of the possibilities, and many more applications utilizing Cyclophon characteristics can of course be envisaged.

IV. Acknowledgment

Acknowledgment is due to E. Labin, who with the authors conducted the original research on the tubes described. Mention should also be made concerning the contributions of A. M. Levine, M. Arditi, and other research engineers of the Federal Telecommunication Laboratories.

V. Appendix

If the total current in a circular homogeneous beam is I, the current i contained in a section A bounded by the aperture edge is

$$i = \frac{4I}{\pi D^2}(A)$$

where A is the area of the section.

The area A may be found by subtracting the triangular area aob from the sectoral area defined by the angle d, so that

$$A = \frac{d}{2}\frac{D^2}{4} - \left(\frac{D}{2} - d\right)(dD - d^2)^{1/2}$$

where

$$\frac{d}{2} = \sin^{-1}\frac{2(dD - d^2)^{1/2}}{D}.$$

So that

$$i = \frac{4I}{\pi D^2}\left[\left(\frac{D^2}{4}\sin^{-1}\frac{2(dD - d^2)^{1/2}}{D}\right) - \left(\frac{D}{2} - d\right)(dD - d^2)^{1/2}\right].$$

Writing d in terms of D so that $d = XD$,

$$\frac{i}{I} = \frac{4}{\pi}\left[\frac{1}{4}\sin^{-1}2(X - X^2)^{1/2} - (1/2 - X)(X - X^2)^{1/2}\right]. \tag{12}$$

A curve of i/I versus $X = d/D$ is shown in Fig. 9.