A METHOD OF PRODUCING A SQUARE WAVE OF RADIO FREQUENCY

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Abstract

A radio-frequency square wave, *suitable for the measurement of the mobility of ions*, has been obtained by using a circuit containing three vacuum tubes. The first tube operates as an oscillator. The potential of the second tube, which operates as a rectifier, is controlled by the grid circuit coil of the oscillator. The third tube is connected so that the plate current will be cut off during the half period when the rectified current is flowing in the plate circuit of tube 2. The rise of the voltage of the square wave is approximately exponential, due to the charge on the grid and the plate of tubes 2 and 3, which must be discharged through a resistance which couples the plate circuit of tube 2 to the grid of tube 3. A cathode ray oscillograph tube indicates that the voltage rises to approximately its maximum value in 1/10 of the half period. A square wave of 120 volts may be obtained with Western Electric "E" tubes. Three methods of amplification are given by which a square wave with a very much larger voltage may be obtained.

Introduction

The apparatus for producing a square wave of radio-frequency has been designed because of the application it has in the measurement of the mobility of ions. The investigations have been confined to vacuum tube methods. The circuits found to be most satisfactory are shown in Fig. 1. Tube 1 operates as an oscillator, so arranged that the mutual inductance of the coils *A*, *B*, *C*, *D*, may be varied. Tube 2 may be regarded as a rectifier and the circuits immediately associated with tube 3 produce the square wave.

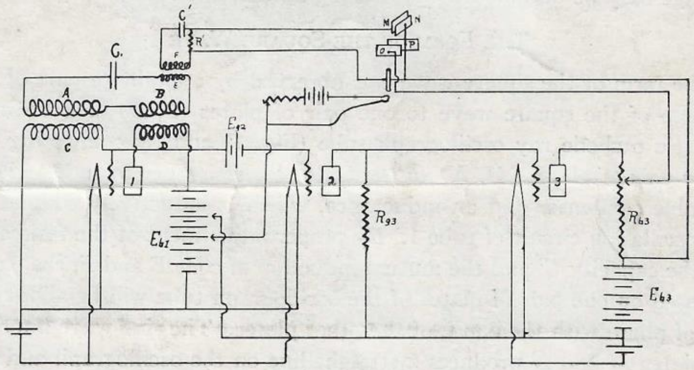

Fig. 1. Diagram of circuit.

METHOD OF OPERATION

The method of operation is as follows. The oscillator imposes an alternating e.m.f. on the grid of tube 2. A certain constant negative potential is placed on the grid by the battery E_{g2} such that during almost one-half of the period the alternating e.m.f. causes the plate current to be cut off. Variations of the plate current impose an alternating e.m.f. on the grid of tube 3. During the time there is no current through R_{g3}, the grid of tube 3 is zero with respect to its filament, and a constant current will flow through R_{b3}, but during the other half period there will be a large negative potential imposed on the grid of tube 3, thus cutting off the plate current. Tubes 2 and 3 must work below the characteristic curve during a part of the period. The square wave thus consists of a sudden rise to a constant voltage and a rapid decrease to zero voltage.

The wave will be very nearly a perfect square if the e.m.f. imposed on the grid of tube 2 is large. This end may be secured without injury to the tube by arranging the circuits as shown in Fig. 1. The grid of tube 2 connects to the grid of tube 1, the potential of which is controlled by the alternating e.m.f. across the grid circuit coil of the oscillator. During the negative half period the grid of tube 2 will reach a very low negative potential, but during the positive half period the rise will be very rapid to about 15 volts, when a current from grid 1 and grid 2 opposes the increase. Therefore the positive half cycle does not increase the grid abnormally. This half cycle, having been amplified and inverted, is imposed on the grid of tube 3. The result is that a square wave of large voltage may be obtained without using an amplifier.

THE FORM OF THE SQUARE WAVE

The form of the square wave was observed by applying a part of the voltage of the square wave to one pair of plates (O, P) of a Western Electric cathode ray oscillograph tube (Fig. 1) and by connecting the other pair of plates (M, N) to the ends of a resistance in series with a variable condenser and an inductance, which is inductively coupled to the oscillation circuit of tube 1. By proper adjustment of the resistance R', the capacity C' and the mutual induction of coils E and F, the e.m.f. imposed on one pair of plates of the oscillograph tube will be about 90° out of phase with the e.m.f. of the other plates. The sine wave imposed on plates M and N produces a straight line on the oscillograph and the square wave produces a straight line at right angles to it. When the difference of phase is about 90° the voltage changes of the square wave take place when the e.m.f. of the sine wave is very near a maximum or a minimum. Thus the electron beam may be deflected to the right by the sine wave, then vertically upward by the square wave then to the left by the sine wave and then vertically downward by the square wave, the entire curve being traced once each period. The photographs of the screen of the oscillograph show the form of the curves thus obtained. Fig. 2 represents 60 volts and Fig. 3 represents 120 volts.

The vertical lines in the photograph are quite indistinct, indicating that the rise and fall of the voltage of the square wave is very rapid. The deflection along the horizontal lines represents a simple harmonic movement of the electron beam, so that the voltage of the square wave changes near the time when the rate of the horizontal deflection is slowest. Therefore the curve obtained in this manner does not represent the exact shape of the square wave which would be obtained by plotting the voltage against the time t.

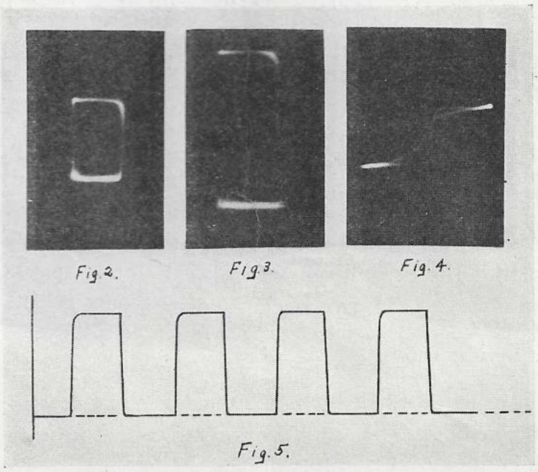

Fig. 2. Fig. 3. Fig. 4.

Fig. 5.

Figs. 2-5. Oscillograph records.

If R' and C' are removed from the circuit and the plates M, N are connected directly to the ends of the coil F, the sine wave voltage and the square wave voltage will be in phase, and the vertical deflections will take place while the horizontal deflections are most rapid. The curve obtained in this manner is shown in Fig. 4. By measuring the horizontal displacement which takes place while the beam is being displaced vertically, the time of rise of the voltage of the square wave was found to be about 1/10 of the half period and the time of fall is about 2/3 of the time of rise. From these observations approximate calculations may be made of the form of the square wave which is represented in Fig. 5.

The form of the square wave depends (1) on the amplitude of the wave imposed on the grid of tube 2; (2) on the capacities of the various circuits and (3) on the voltage amplification factor of tube 2. Using Western Electric "E" tubes, with circuit constants to be given later, the time required for the original wave to vary over a range sufficient to produce the square wave was about 1/20 of the period of oscillation.

The rate of rise of the voltage of the square wave decreases as the capacity of the circuits and tubes is increased. Due to these capacities the voltage changes will be approximately exponential, as the charge on the plate and the grid is being discharged through the external resistance of the plate circuit. The voltage will increase rapidly at first, but as the grid potential approaches a limiting value the rate of increase gradually becomes less. A slight bend showing this effect can be observed in the photographs of the curve (Figs. 2 and 3). As the voltage of the square wave decreases, the grid of tube 3 reaches its limiting potential after the current in the plate circuit has been cut off. This eliminates a part of the capacity effect, so that the time of fall will be less than the time of rise of the voltage.

The capacity in series with R_{g3} consists of the capacity of the plate and the filament and of the plate and the grid of tube 2 and the capacity of the grid and the filament and of the grid and the plate of tube 3. As the grid varies in potential the plate also varies but with the opposite potential, so that the total discharge through R_{g3} is of such magnitude that the square wave will be appreciably distorted if R_{g3} should be more than 2000 ohms when E_{b3} is 200 volts, but for higher plate voltages it has been found empirically that R_{g3} may be approximately equal to $R_{b3}+R_0)/\mu_0$ in which R_0 is the internal impedance of the tube and μ_0 is the amplification constant. The amplification factor μ of tube 2 will be small, as can easily be observed by plotting the voltage across R_{b3} against the grid voltage, or it may be obtained approximately from the relation $\mu=\mu_0 R/(R+R_0)$.[1] The rate of rise of the voltage of the square wave, due to an increase of the amplification factor, is opposed by the capacity effects of the tube, thus requiring proper adjustment of R_{g3} to obtain the best wave form.

CONDITION FOR BEST OPERATION

If we desire to produce a square wave for any assigned purpose it is necessary to determine (1) the voltage which is to be obtained from the square wave; (2) the current that can be taken off without too great

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[1] Van Der Bijl, Proc. I nst. Radio Eng. **7**, 97 (1919)

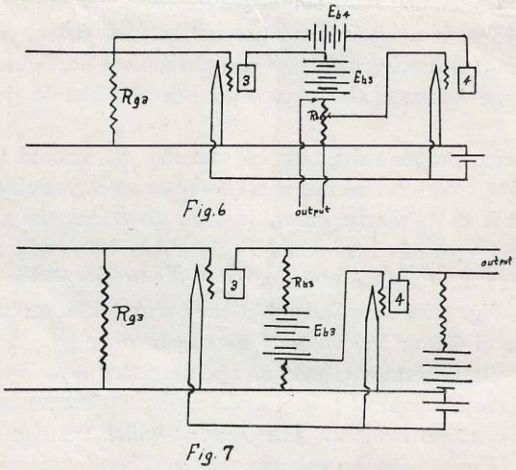
change of voltage; and (3) the resistance which can be used in the circuit to which the apparatus is coupled so that the added capacities will not distort the wave form. In order to keep the resistance small the impedance of the tubes should be small. The best operation is found by making R_{b3} about equal to the impedance of the tube. The voltage of the square wave obtainable will then be about 1/2 of E_{b3}. It may be increased to 2/3 of E_{b3} by increasing the resistance R_{b3}. Or it may be increased by making E_{g3} positive, say 10 volts or even more as a grid current through R_{g3} causes no appreciable disturbance. The tube may even be operated up to the saturation point of the curve, which is quite low when the resistance R_{b3} is large. The actual square wave voltage thus obtained with "E" tubes, was 200 volts by using 375 volts on the plate. The voltage E_{b3} may be increased above its normal operating value, since there is a large resistance in the grid circuit and because the plate current is flowing only half-one of the time and when it is flowing the voltage between the plate and the filament is decreased to (E_b-RI).

After choosing proper values for E_{b3} and R_{b3}, R_{g3} should be approximately equal to $(R_{b3}+R_0)/\mu_0$ but it is better to use a variable resistance and to adjust it to its maximum value while observing the shape of the wave. Tube 1 operates best when E_{b1} is about 180 volts, and tube 2 operates successfully with a plate voltage of 140 volts. Plate batteries are shown in Fig. 1 for simplicity, but they may all be replaced by one d.c. generator of 400 or 500 volts. This can be done by placing a large resistance in the generator circuit and joining the negative end of the resistance to the filament of tube 1 and tapping off the desired voltages to the plates of tubes 1 and 2. The point at which the circuit from the plate of tube 2 connects to the resistance in the generator circuit is directly connected to the filament of tube 3, so that the desired plate voltage for tube 3 may be obtained by tapping off at a point of higher potential. If an oscillograph tube is used to observe the wave form, the generator may also be used to place a suitable potential on the anode similar to the connections shown in Fig. 1. The adjustment so that each half period of the wave is equal, is made by varying the voltage on the battery E_{g2}, which should be about 20 volts negative. The oscillator should produce a voltage across the condenser of about 450 volts. The frequency used was about 100,000 but the wave form is almost as good up to 600,000, which is as high as trials were made.

The resistance should be as non-inductive as possible, though ordinary resistance boxes are quite successful. Very good results were obtained by using resistances made of quartz fiber sputtered with platinum and mounted in oil.[2] It is essential that capacities in all circuits be made as small as possible. If the connections are made as shown in Fig. 1, the capacity effects between the batteries will be largely eliminated. If the batteries are replaced by a generator, a condenser should be placed in parallel with each part of the resistance of the generator circuit which is placed in a plate circuit.

METHODS OF AMPLIFICATION

If a square wave having an e.m.f. of more than 150 volts is desired, amplification may be obtained by either of the three following methods. The voltage of the rectified wave of tube 2 may be increased by placing another tube in parallel with it, making it possible to increase the voltage on the plate of tube 3. Another method (Fig. 6) is to place the extra tube so that the grid is operated from a part of the voltage across R_{b3}, and to connect the plate in series with R_{g3}. In this way the negative range of potential of the grid of tube 3 is greatly increased, since the current in the plate circuit of tube 4 is added to the current of the plate circuit of tube 2. In fact the amount of current fed back into the grid circuit of tube 3 can easily be adjusted so that a very small range of the original wave imposed on the grid of tube 3 is necessary to produce a square wave of good form. This method will be very useful if for any reason the amplitude of the original wave is small. The voltage of E_{b4} should be



Figs. 6-7. Circuits used for amplification.

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[2] Frayne, Phys. Rev. **21**, 348 (1923)

about 1/2 of E_{b3}. Another method of amplification is to add another tube (Fig. 7) to be operated similarly to tube 3 by imposing a part of the voltage across R_{b3} on the grid of tube 4. The total voltage obtained by this method, when R_{b3} and R_{b4} are placed in series in the circuit in which the square wave is to be used, will be the sum of the voltages across R_{b3} and R_{b4}. If this method is combined with the first method of amplification given, a very large voltage may be obtained.

In conclusion I wish to express my thanks to Prof. W. F. G. Swann for suggesting the problem and for the valuable assistance he has given. I also wish to thank Dr. F. M. Kannenstine for the suggestions he has offered. The investigation has been made possible by the courtesy of Dr. E. H. Colpitts of the Western Electric Co., who loaned the tubes which were used in the experiments.

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