Dec. 11, 1945. D. P. COLE 2,390,777

FREQUENCY MODULATION SYSTEM

Filed March 10, 1942 2 Sheets-Sheet 1

Fig. 1.

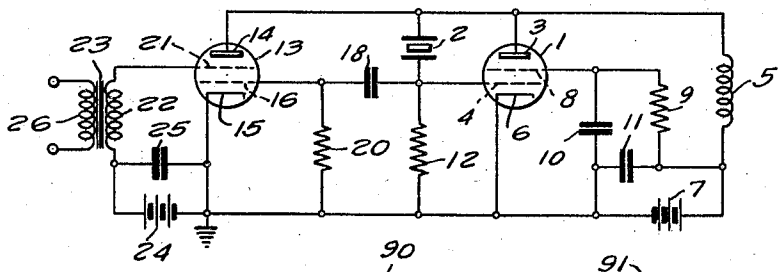
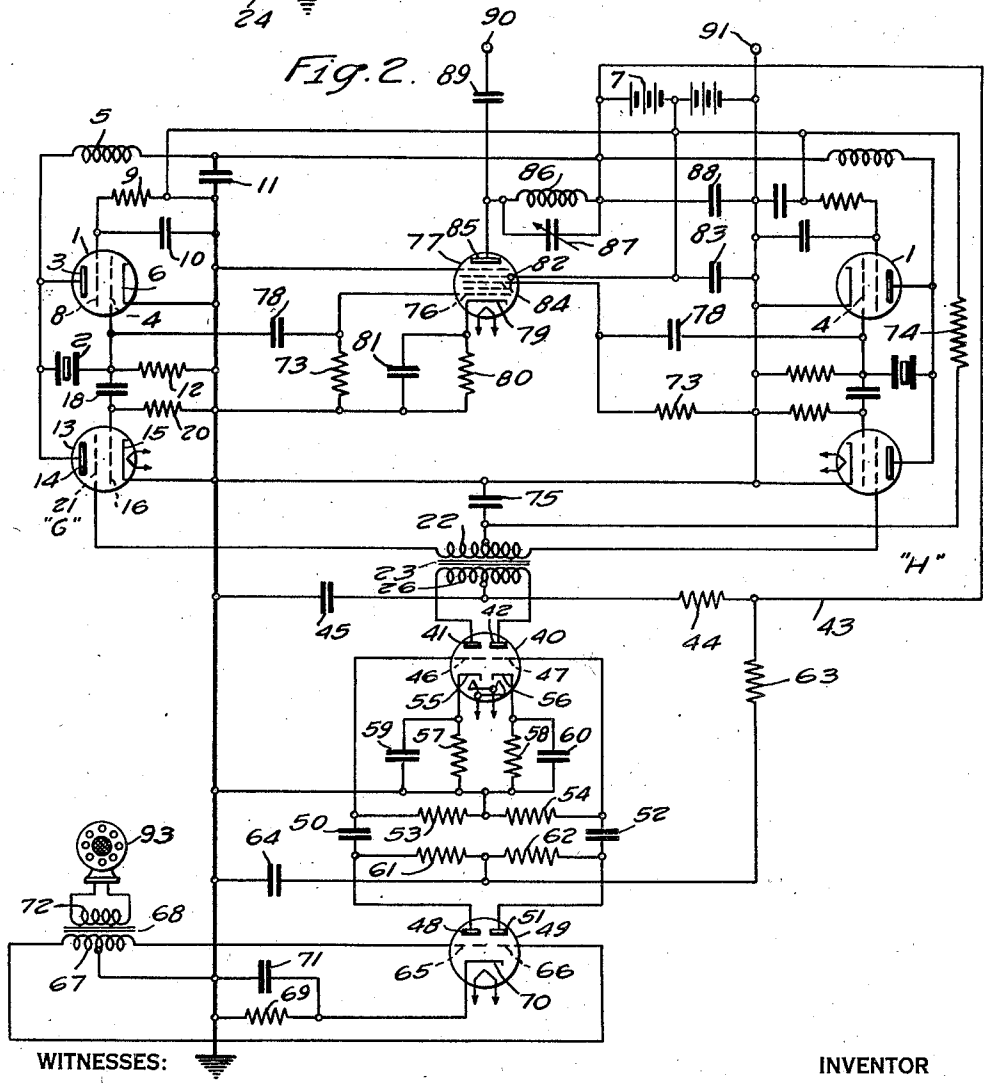


Fig. 2.



WITNESSES:

E. A. McCloskey.

T. S. Bartley

INVENTOR

Donald P. Cole.

BY

Hyman Pearl

ATTORNEY

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Fig. 3.

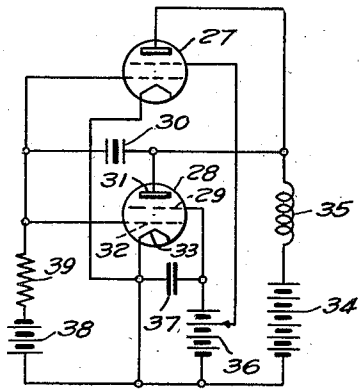


Fig. 5.

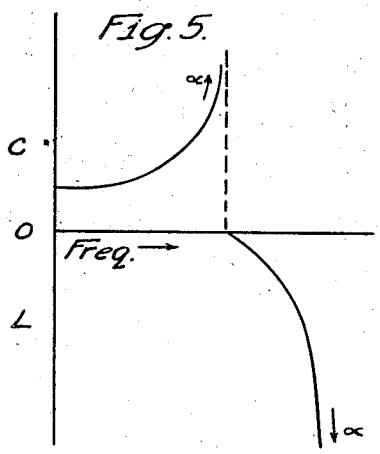


Fig. 7.

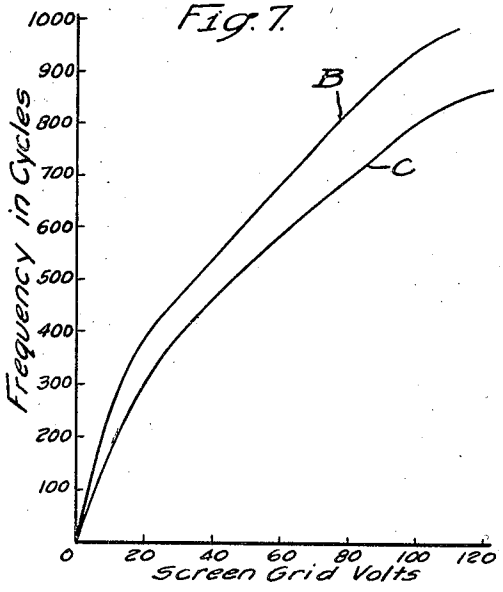


Fig. 8.

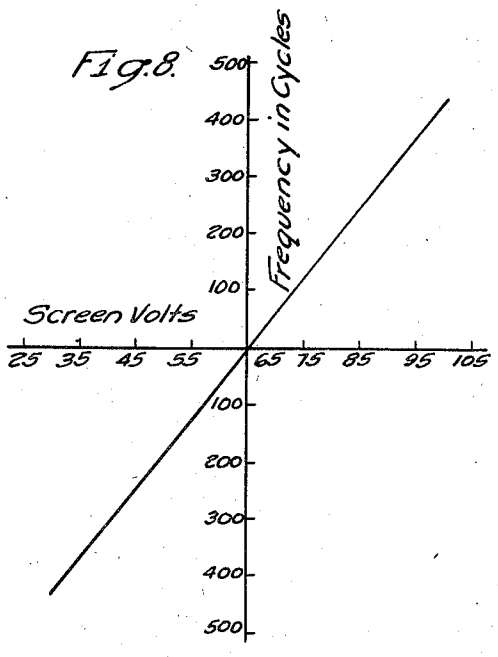


Fig. 6.

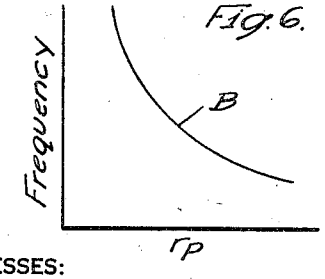
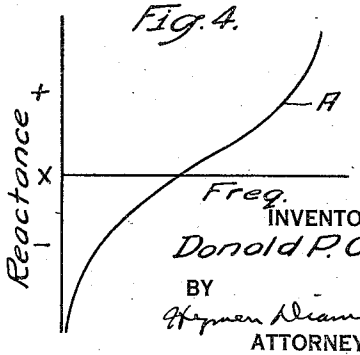


Fig. 4.



WITNESSES:

E. A. McCloskey.

H. E. Barthold

INVENTOR

Donald P. Cole.

BY

Hopman Diamond

ATTORNEY

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UNITED STATES PATENT OFFICE

2,390,777

FREQUENCY MODULATION SYSTEM

Donald P. Cole, Catonsville, Md., assignor to Westinghouse Electric Corporation, East Pittsburgh, Pa., a corporation of Pennsylvania

Application March 10, 1942, Serial No. 434,033

1 Claim. (Cl. 179—171.5)

This invention relates to modulation systems, and particularly to radio transmitting systems of the type in which the radiated power is held constant while the carrier frequency is varied in accordance with the signals to be transmitted.

In frequency modulation systems, the modulation comprises the deviation from a certain predetermined operating frequency in proportion to the intensity of the modulation signals, such for example, as speech or music, and at a rate of the frequency of the modulation signal. The energy radiated is not changed in amplitude, only the carrier frequency changes with the instantaneous variations of the intensity of the signals to be transmitted.

There are various methods known whereby the frequency output of a vacuum tube oscillator may be varied. It is important, however, that the unmodulated carrier shall always have the exact predetermined value which is set for the operation of the transmitter. The greatest accuracy in frequency stability of an oscillator is obtained when the frequency determining element is a vibratile device, such for example, as a piezo-electric crystal. In view of the fact that a crystal tends to maintain the oscillations generated at a constant frequency, determined by the physical size of the crystal element, the frequency deviation may be obtained only within very narrow limits from the crystal frequency. Various attempts have been made in the prior art to cause frequency deviation of a crystal controlled oscillator for the purpose of modulation. The narrow limits of frequency deviation made such attempts unsuccessful from a practical standpoint.

A particular feature of this invention is that comparatively wide frequency deviation may be obtained in the transmission system while extreme frequency stability is maintained as to the operating carrier frequency by means of a piezo-electric crystal device.

Another feature of this invention is that a plurality of crystal controlled oscillators may be utilized and the individual frequency deviation due to modulation of the oscillators may be combined to increase the total effective frequency deviation.

An advantage of the modulation system herein described is that within the present range of frequency modulation transmission in the neighborhood of 50 megacycles, crystals of such physical parameters may be chosen which give the maximum useful range of crystal frequency deviation.

Other features and advantages will be apparent from the following description of the invention, pointed out in particularity by the appended claim and taken in connection with the accompanying drawings, in which:

Figure 1 is a schematic circuit diagram of the oscillator and modulator portion of the system;

Fig. 2 is a schematic circuit diagram of the complete modulation system including two identical oscillator and modulator portions;

Fig. 3 is a simplified reference diagram to be used in connection with the theoretical consideration of the system;

Figs. 4, 5 and 6 are curves illustrating certain relations forming the bases of the theoretical consideration with reference to Fig. 3;

Fig. 7 shows the variation of frequency obtained with the modulation system shown in Fig. 1 by means of changes of the screen grid voltage of the modulator tube; and

Fig. 8 shows the linear relation of the useful range of frequency shift obtained from the combination of the two oscillators shown in Fig. 2 when the screen voltage of each modulator tube is varied.

Referring to Fig. 1 of the drawings, vacuum tube 1 is connected in an oscillating circuit having as the sole frequency determining element, a piezo-electric crystal 2 placed between anode 3 and control electrode 4. The anode circuit of the oscillator includes the inductance 5 connected between the anode 1 and cathode 6 in series with the anode potential source shown here by the battery 7. The screen-grid 8 of the tube 1 is supplied with the required potential from the battery 7 through a screen-grid resistor 9. The high frequency currents are suitably bypassed by the condenser 10 in the screen-grid circuit and by the condenser 11 in the anode circuit. The grid 4 returns to the cathode by means of the grid-load resistor 12.

The circuit so far described is a conventional type of crystal controlled oscillator in which the crystal forms the coupling means between the anode and the grid circuits, as well as the frequency determining element. In this manner, the oscillator does not depend upon feedback either through external coupling between the anode and the grid circuits, or by coupling provided by the inherent inter-electrode capacity of the tube.

The modulator for producing a deviation from the static crystal frequency comprises a second vacuum tube 13 which is connected substantially in parallel with the tube 1 in that the anode 14 is connected to the anode 3, the cathode 15 to

the cathode 6, and the grid 16 to the grid 4, the latter by means of a coupling condenser 18. The grid 16 returns to the cathode 15 through grid resistor 20. The screen grid 21 of the tube 13 is utilized as an additional control electrode, being connected to the secondary winding 22 of the transformer 23. An initial screen-grid potential is supplied from the battery 24 connected between the cathode 15 and the return terminal of the winding 22. Condenser 25 forms the bypass for the modulation frequency currents.

The terminals of the primary winding 26 of the transformer 23 may be connected to any suitable source of modulation frequency currents, such as the output of a speech amplifier if voice transmission is contemplated. Any suitable manner of coupling may be utilized as long as the voltage input between the terminals of the primary winding 26 is of suitable magnitude to impress upon the screen-grid circuit sufficient voltage to vary the effective potential on the screen-grid electrode 21 within the required limits, as will be described later.

The circuit of Fig. 1 represents the oscillator and modulator portion of the combined system shown in Fig. 2 of the drawings. In the latter, two complete oscillator and modulator portions, as shown in Fig. 1, are combined in one circuit in a push-pull type arrangement as to the modulation voltage input. The output voltages of each, on the other hand, are mixed in a common output circuit. For a better understanding of the function of the frequency modulation system shown in Figs. 1 and 2, a series of elementary theoretical diagrams are included in the drawings, to which reference shall be had prior to discussing the complete system of Fig. 2.

Referring to Fig. 3, let it be assumed first that the tube 27, which is in parallel with the tube 28, is omitted and we are considering only the tube 28 and its associated circuits. We may also regard, for the purpose of analysis, tube 28 basically as a three-electrode vacuum tube although a tetrode is shown here. The purpose of the screen grid electrode 29 is merely to reduce the grid-to-plate capacity. The effective grid-to-plate capacity, on the other hand, is now supplied by the crystal element 30, which is connected between the anode 31 and grid 32 of the tube 28. The circuit between the anode 31 and the cathode 33 is similar as to its components to the one shown in Fig. 1, in that plate potential is applied from the battery 34 through the inductance 35 between anode 31 and cathode 33. Screen grid potential is derived from the battery 36 and the screen grid electrode 29 is suitably bypassed by the condenser 37. The grid circuit includes the bias battery 38 and the grid resistor 39.

Neglecting for the moment the effect of the resistance 39 and applying a voltage which varies with time between grid 32 and cathode 33, it will be found that the impedance presented to this voltage is a negative value of input resistance. The value of this resistance can be calculated by referring to the equation (57) on page 209 in the book "Thermionic Vacuum Tubes" by Van der Bijl. This gives for a pure inductance in the output circuit the following value for the input resistance.

$$R_g = -\frac{L_o C_3}{R_p (C_1 + C_3)^2}$$

where Rg=the input resistance, Rp=the anode resistance, Lo=the anode circuit inductance, C_1=the grid cathode capacity and C_3=the grid anode capacity. Now, if the value of this input resistance is lower than that of the parallel positive resistance, the net input resistance will be negative and the tube will oscillate.

Referring now to Fig. 4, curve A shows the reactance which a piezo-electric crystal presents when a voltage which varies with time is applied to it. From this, we can calculate the apparent capacity or inductance of the crystal circuit as the frequency varies. This is shown in Fig. 5. It is seen here that at some frequency the capacity as presented by the crystal circuit will be of the value required to make the negative input resistance of the tube 28 and its associated circuit equal to the positive resistance. This point on the frequency ordinate is shown by the dotted line. The net losses will now be zero, permitting the circuit to oscillate. If the plate resistance of the tube 28 is caused to vary by some means, it is apparent from the equation above referred to that the grid plate capacity must change in order that the negative input resistance shall be exactly equal to the positive circuit resistance. This holds true because the positive circuit resistance cannot change since it is a circuit element and the condition for oscillation is that the negative input resistance must equal the positive circuit resistance. Thus, from the equation, it is apparent that if any one element changes, some other element must change to keep the input resistance constant. Now, since the amplification factor, the output inductance and the grid to filament capacity are geometrical constants, it is apparent that when the plate resistance is changed, the grid plate capacity must change to keep the input resistance constant.

We may now consider the second tube 27 in parallel with the tube 28. A parallel connection, as shown in Fig. 3, will change the plate resistance of the circuit. This is evident since the total amplification factor remains unchanged. Furthermore, the grid-to-filament capacity of tube 27 being always in parallel with the grid-to-filament capacity of the tube 28, does not change with variations of screen grid potential on the parallel connected tube. It is readily seen that if we change the screen grid potential of the tube 27, as indicated by the adjustable connection on the battery 36, the plate resistance of the tube, as well as the grid plate capacity, must change in order to maintain equilibrium. We have seen in Fig. 5 that the capacity of the crystal will vary with changes of frequency. Hence, by the same consideration the frequency of the oscillations will vary. This variation follows directly in accordance with the calculations employing the equation above referred to. The resultant variation of frequency with variation of screen grid potential is shown in Fig. 6 of the drawings, in which curve B indicates a change of frequency with a change of plate resistance.

From the above theoretical analysis it is seen that in the modulation system in accordance with this invention the frequency deviation of a crystal controlled oscillator is obtained by variation of the effective plate resistance of the oscillator tube. To vary the effective plate resistance in accordance with signal amplitudes the modulator tube is effectively connected in parallel with the oscillator tube and an auxiliary control electrode thereof, such as the screen-grid electrode, is utilized for modulation signal input.

When the screen-grid circuit of the modulator tube 13 in Fig. 1 or tube 27 in Fig. 2 receives no excitation, a static condition exists and the oscil-

lator frequency will have a certain value depending upon the physical parameters of the crystal 2. The expression "static frequency" is chosen to define the frequency from which any departure is caused by modulation. The output of the oscillator may be taken off from either the anode circuit or the grid circuit to be utilized in the transmission system.

Reference should now be had to Fig. 7, in which the change of frequency from the static frequency is plotted as a function of screen-grid voltage. It is seen that in the region when the screen-grid potential varies from about 30 volts to 100 volts, the frequency change is linear. Curve C is drawn for a static frequency of 2942.5 kilocycles, whereas curve B is drawn from a static frequency of 2557.5 kilocycles. In both curves, a considerably large straight-line portion of frequency shift may be observed. The useful range represented by the straight portion gives in total shift for one crystal approximately 400 to 500 cycles. In present practice of frequency modulation transmission, this order of frequency shift would not be practical since it is generally desired that the carrier output frequency deviation should be approximately 200 kilocycles with a carrier frequency between 40 and 50 megacycles. With only 400 cycles available frequency shift of one oscillator, the frequency would have to be multiplied 500 times and the static oscillator frequency would have to be between 80 to 100 kilocycles to cover the proper range. Piezo-electric crystals in this range are difficult to make and are sluggish in response.

In order to effectively employ the simple frequency modulation circuit in accordance with this invention, in a transmitting system operating in the 40 megacycle wave band with wide band frequency deviation, two oscillators are combined each with its associated modulator tube in such manner that the output of each will be additive as to total frequency deviation. This arrangement is shown in Fig. 2 of the drawings, in which identical components in the oscillator circuits with respect to Fig. 1 bear similar reference characters. The first oscillator modulator stage is indicated by G and the second similar stage by H. In the first stage, vacuum tube 1 comprises the oscillator proper having its anode 3 connected to suitable impedance 5 which terminates at the high potential side of the power supply source represented by the battery 7, which is bypassed by means of the condenser 11. The screen-grid electrode 8 bypassed by the condenser 10, returns in series with the screen-grid resistor 9 to a suitable voltage tap of the battery 7. The cathode 6 of the oscillator tube is connected to ground, which is indicated by a heavy line throughout in the figure. Between the anode 3 and grid 4 is connected the crystal 2. The grid circuit returns to ground through the grid resistor 12. The modulator tube 13 is effectively in parallel with the oscillator tube having its anode 14 connected to the anode 3 and its cathode 15 to ground. The grid 16 thereof is capacitively coupled by means of the condenser 18 to the grid 4 of the oscillator tube 1. The grid circuit returns to ground through grid resistor 20. The screen grid 21 acting as a control grid connects to the secondary winding 22 of the modulation frequency transformer 23.

The second oscillator stage H is identical in every detail with the one just described. Corresponding elements thereof are marked with identical reference characters. Since this oscillator stage is in all details and function similar to the one previously described it is not believed necessary to repeat the circuit description. The combined function of the modulated oscillator stages H and G will be considered in detail when referring to the operation of the system.

The modulation voltage is fed to the primary winding 26 of the transformer 23 from a preceding pushpull amplifier stage shown here by the dual triode tube 40. The anodes 41 and 42 thereof terminate in the free ends of the winding 23, the center tap of which is supplied with the required anode potential from the high potential side of the battery 7 through the conductor 43. A series resistor 44 is included and the center tap of the winding 26 is bypassed by the condenser 45. The grids 46 and 47 of the tube 40 are excited with modulation frequency currents from the output of another amplifying stage, the grid 46 being coupled to the anode 48 of the tube 49, through coupling condenser 50, whereas the grid 47 is coupled to the anode 51 by means of coupling condenser 52. Resistor 53 is connected to the grid 46 and returns to ground. The resistor 54 similarly connects to the grid 47 and returns to ground. The cathode 55 and the cathode 56 of the tube 40 each return to ground through suitable bias voltage resistors 57 and 58, respectively, bypassed by the condensers 59 and 60.

The anode circuit of the tube 49 includes the load resistor 61 for the anode 48 and the load resistor 62 for the anode 51 terminating in the anode supply source by means of the series resistance 63 which is bypassed by the condenser 64. The input circuit of the tube 49 between grids 65 and 66 includes the secondary winding 67 of the input transformer 68. The center tap thereof returns to ground. Bias voltage for the grids is derived by the cathode resistor 69 which connects to the cathode 70 of the tube 49 and ground. The latter is bypassed by the condenser 71. The primary winding 72 of the transformer 68 is shown here as being connected to a microphone 93 which is the ultimate source of modulation voltage. While there are only two audio frequency stages shown between the microphone and the modulator tubes, it is to be understood that these are merely by way of example to indicate that suitable amplification of the microphone currents must be provided in order to raise the output voltage to the level necessary for swinging the screen-grid electrodes 21 within the limits of screen voltage change giving linear responsive to the frequency variation of the oscillator. The screen-grid electrodes 21 of the tubes 13 in stages G and H, are of course supplied with the acquired operating potentials from the top on the battery 7 which also supplies the screen-grid electrodes 8 of the oscillator tubes 1. A connection from the midpoint of secondary winding 22 of the modulation input transformer 23 is connected through filter resistor 74 to the screen protective top of the battery 7. The condenser 75 forms the modulation frequency bypass between ground and the midpoint of the winding 22.

Further analysis of the circuit will show that both oscillator modulator stages G and H are connected in push pull relation so that the modulation excitation voltage is 180° out of phase between screen grids 21. Consequently, while in one stage the voltage is increasing from the initial voltage supplied by the battery; in the other stage it will be proportionately descreasing in the same amount provided that balance is maintained in the push pull circuit. From this it is also seen that in one stage the oscillator output frequency

will be increasing from a predetermined value whereas in the other stage, it will be decreasing from another predetermined value. This condition is better understood when referring to Fig. 8, which shows the frequency deviation of oscillators G and H plotted against change in screen voltage. The effective change in each within the voltage limits for the screen grid is identical and linear giving approximately 400 cycles total shift. The output frequency of each oscillator may be so combined that the frequency shift of one oscillator will add to the frequency shift of the other with respect to the ultimaely derived ouput frequency deviation.

Now then, if such combination is achieved as will be seen with further reference to Fig. 2, a total shift of approximately 800 cycles may be obtained. The push pull excitation of the two modulator tubes provides for the proper phase displacement between the oscillator voltages which are derived from the grid circuit of each oscillator tube. In the oscillator stage G the grid 4 is coupled to the first control grid 76 of the mixer tube 77 by means of the condenser 78 terminating at the grid load resistor 73 which returns to ground. The tube 77 is of the multi-grid type widely used for mixing purposes. The cathode 79 thereof returns to ground through the conventional bias resistor 80 bypassed by the condenser 81. The screen grid 82 bypassed by the condenser 83 is supplied with suitable potential from the screen-grid voltage top of the battery 7. The second grid, generally referred to as the injector grid 84, is coupled to the grid 4 of the oscillator tube 1 of the stage H in the same manner as the control grid 4 of the oscillator stage G, namely by means of the coupling condenser 78 and grid load resistor 73.

The anode circuit of the tube 77 between the anode 85 and cathode 79 includes the parallel tuned circuit comprising the inductance 86 and the condenser 87, terminating at the high potential side of the battery 7. The return terminal of the inductance is bypassed by the condenser 88. The output of the mixer tube 77 for further utilization is obtained by means of capacity coupling through the condenser 89, between terminals 90 and the ground terminal 91.

In the operation of the system, the static frequency of the oscillator tube 1 and in stage G of tube 1 in stage H is so chosen as to give a suitable value of difference frequency in the output circuit of the mixer tube which, when further multiplied by means of frequency multiplying stages in accordance with conventional practice, will result in the designated operating frequency for the transmitting system. Therefore, in the mixer tube the output circuit is designed to be resonant to the difference frequency of the two oscillators, and is tuned to resonance by means of the condenser 87.

In a practical embodiment of the modulation system herein described, the static crystal frequency for the oscillator tube of stage G was chosen to be 2942.5 kilocycles and for the oscillator tube of stage H 2557.5 kilocycles. The resultant frequency difference was 385 kilocycles. The modulation of both oscillators resulted in a linear frequency shift of approximately 500 cycles for each, which, by means of the push pull circuit arrangement in combining the oscillator frequency, doubled to 1000 cycles. In this manner, a multiplication in the order of 250 times was only necessary to operate in the 40 or 50 megacycle band. It is to be noted here that without the push pull circuit and mixer stage, the useful frequency shift would be only 400 cycles and this would have to be multiplied 500 times to cover the assigned frequency range. This means also that the oscillator static frequency would have to be between 80 to 100 kilocycles. In this frequency range, crystals are also sluggish in operation and are difficult to make.

I claim as my invention:

In a frequency modulation system, a vacuum tube oscillator having anode, cathode and control electrodes, a vibratile frequency determining element connected between said anode and control electrode, means for causing frequency deviation of said oscillator in proportion to modulation signal intensities and at a signal frequency rate, said means including a second vacuum tube having an anode, a cathode and a plurality of control electrodes, the last mentioned anode and cathode being connected respectively to the corresponding electrodes of said oscillator tube and one of the last-mentioned control electrodes being capacitively coupled to the control electrode thereof, an input circuit between the other control electrode and cathode of said second vacuum tube, said circuit being energized with modulation signals.

DONALD P. COLE.