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S. W. LEWINTER

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PHASE MODULATION SYSTEM

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FIG. 1.

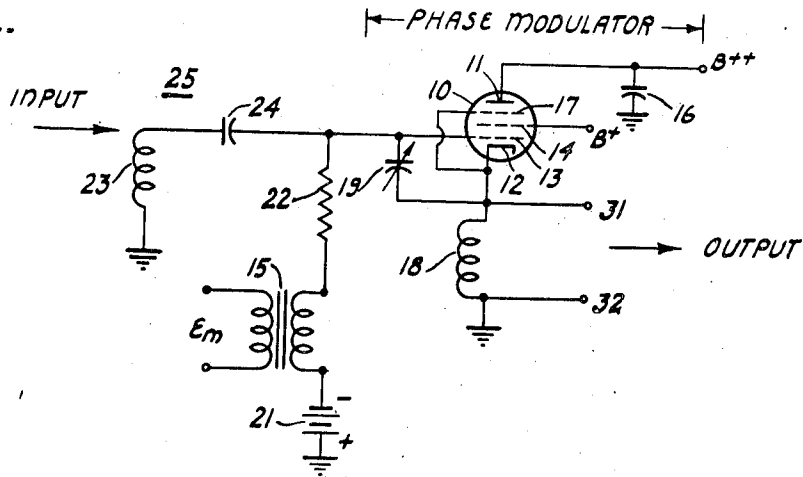


FIG. 3.

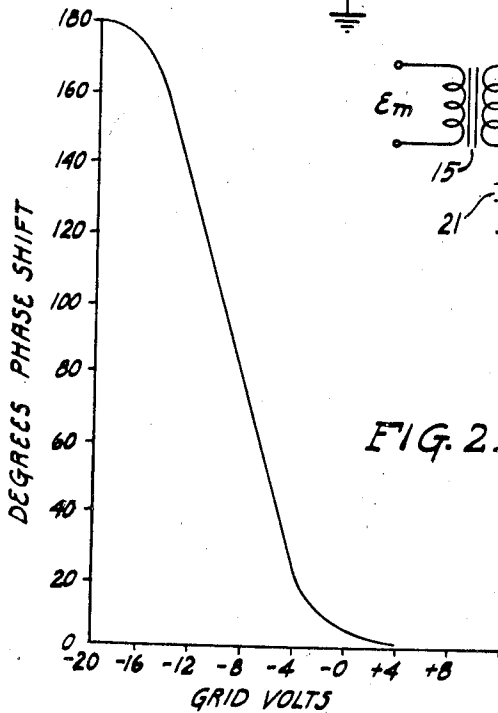
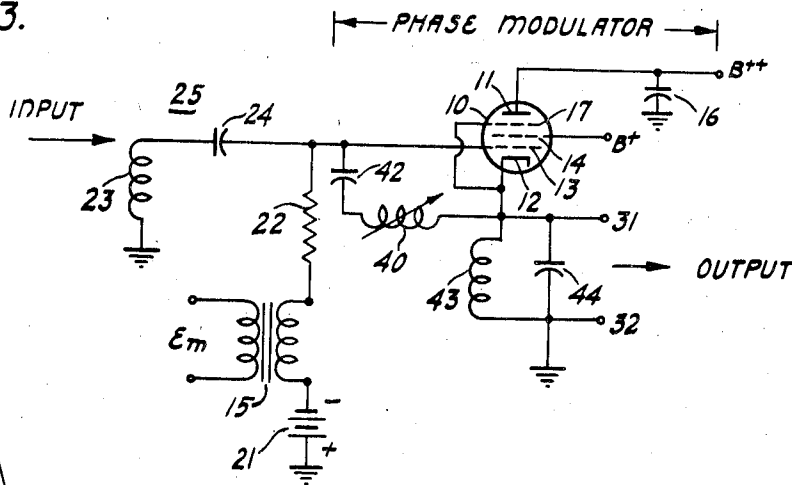


FIG. 2.

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PHASE MODULATION SYSTEM

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8 Claims. (Cl. 332-27)

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The invention herein described and claimed relates to a phase-modulation system, and particularly to an improved phase-modulator circuit capable of providing substantially linear phase modulation over a relatively wide range, which, in the preferred embodiment, is substantially free of undesired amplitude modulation.

The circuit of the present invention is very simple and employs but a single vacuum tube, which may be of standard construction; yet linear phase variations are achieved over a deviation range substantially wider than has heretofore been attained prior to the frequency-multiplication stages unless relatively expensive special tubes and complicated circuits be employed.

Frequency-multiplication and heterodyning may also be employed, or even required, in connection with my novel phase-modulator in order to further widen the deviation range to usable magnitude, but linear phase variations of the order of 140° , i. e. plus and minus 70° , are attained prior to any multiplication of frequency. This is substantially wider than has been heretofore attained without the employment of costly apparatus.

It is an object of this invention to provide relatively simple, inexpensive means capable of producing substantially distortionless phase modulation over a relatively wide range.

It is another object of this invention to provide means for producing substantially linear phase modulation over a relatively wide range prior to the employment of frequency multipliers.

It is a further object of this invention to provide means for producing substantially linear phase modulation over a relatively wide range prior to the employment of frequency multipliers and without simultaneously producing undesired amplitude modulation.

These and other objects, advantages and features of my invention will become clear from a consideration of the following detailed description of the accompanying drawings wherein:

Figure 1 is a schematic illustration of a circuit comprising one form of phase modulator embodying my invention;

Figure 2 shows the phase-shift characteristics of my improved circuit; and

Figure 3 is a schematic illustration of a modified form of phase-modulator embodying my invention.

Referring now to Figure 1, there is shown a vacuum tube 10, which may be a pentode, having anode 11, cathode 12, control grid 13, screen grid 14 and suppressor grid 17. Anode 11 and screen

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grid 14 are connected to sources of fixed positive potential which may be of the order of 180 volts and 120 volts, respectively. Capacitor 16 functions as a by-pass capacitor. Suppressor grid 17 is connected to cathode 12 and both are grounded through inductance coil 18 which offers high impedance to carrier frequencies but offers negligible impedance to modulating frequencies. The Q of coil 18 is high, preferably of the order of twenty or more. The inductance value of coil 18 is preferably such that its reactance at carrier frequencies is very high in comparison with the minimum value of the inverse mutual conductance, $1/G_m$, of tube 10. The optimum inductance value of coil 18 is dependent upon the grid-volts versus mutual-conductance characteristic of the particular tube employed, as will be more fully discussed hereinafter.

Tube 10 is preferably, although not necessarily, a variable- μ tube having a high amplification factor. An example of a tube having very excellent characteristics for this purpose is the pentode identified commercially as type 9003, but as indicated above, tubes having less desirable characteristics may be used. In some of the experiments which I conducted, a type 6J5 triode was used and produced very satisfactory results. This tube is not a variable- μ tube and has an amplification factor of twenty.

Referring again to Figure 1, the value of capacitor 19, connected between control grid 13 and cathode 12, is such that its reactance at carrier frequencies is greater than that of inductance coil 18, preferably twice as great, for reasons that will become clear. Capacitance 19 offers very high impedance to modulating frequencies.

Control grid 13 is negatively biased with respect to ground, as by battery 21; the bias voltage is applied by way of the secondary winding of coupling transformer 15 in series with grid resistor 22. Transformer 15 couples the modulating voltage source E_m to the grid of tube 10 through resistor 22. Coil 23 and capacitor 24 comprise a carrier-frequency input circuit 25. The capacitance of capacitor 24 is ordinarily much larger than that of capacitor 19. The impedance of input circuit 25 is low, preferably much smaller than the smallest input impedance of the phase-modulator (Figure 1) at carrier frequency. The manner in which the input impedance of the phase-modulator circuit varies with the modulating signal will be described hereinafter. The carrier-frequency input may desirably have its source in a stable oscillator, such as a crystal oscillator (not shown).

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The operation of the circuit of Figure 1 will now be described. Consider first an unmodulated wave of substantially constant carrier frequency applied to control grid 13 by way of input circuit 25. The current flowing through coil 18 will be comprised of two components, (a) the carrier-frequency current from the input source 25 flowing through coil 18 by way of the total grid-to-cathode capacitance, and (b) a carrier-frequency current having its source in tube 10. Component (b) flows through a series circuit which includes the internal output impedance of tube 10, capacitor 16, ground, and inductance coil 18.

The total grid-to-cathode capacitance, referred to above, comprises capacitor 19 and the grid-to-cathode inter-electrode capacitance. The latter will ordinarily be very small in comparison with the magnitude of capacitor 19.

Assume now a modulating voltage E_m to be applied through transformer 15 and resistor 22 to control grid 13. The effect of this voltage is to vary the bias on tube 10 about the fixed operating bias provided by battery 21. Care is to be exercised in the selection of the fixed operating bias, and in the preferred embodiment, this point is located on the lower portion of the grid-volts versus plate-current characteristic of tube 10. If tube 10 be a variable- μ tube, the lower portion of this characteristic is long and curving and approaches cut-off slowly at a non-linear rate. The mutual conductance, G_m , of tube 10 will thereupon vary non-linearly as a function of the applied modulating signal.

The manner in which the mutual conductance G_m varies may be indicated generally as follows: As the modulating voltage E_m approaches a maximum negative value, tube 10 approaches close to cut-off, the mutual conductance G_m of the tube approaches zero, and the plate current is substantially zero. As the modulating voltage E_m approaches a maximum positive value, the G_m of tube 10 attains a maximum value and a heavy plate current flows through coil 18. Intermediate these two extremes of modulating signal, the G_m of the tube and the magnitude and phase of the plate current vary over a range of intermediate values as a function of the applied modulating signal.

When the modulating signal is a maximum negative value, and the mutual conductance G_m of tube 10 is zero, or at least very small, the phase-modulator portion of the circuit of Figure 1 reduces to a capacitance-inductance voltage-divider network in which the capacitance is comprised of the total grid-to-cathode capacitance, including capacitor 19, and the inductance is comprised of coil 18. If the relationship between the capacitance and inductance values of the voltage-divider circuit be such that, at the operating carrier frequency, the reactance of coil 18 be smaller than that of the total grid-to-cathode capacitive reactance, then the carrier-frequency voltage appearing across coil 18 will be 180° out of phase with the carrier-frequency input voltage. And if the reactance of coil 18 is one-half that of the grid-to-cathode capacitive reactance, the carrier-frequency voltage developed across coil 18 will not only be 180° out of phase with the carrier-frequency input voltage, but will also be equal in magnitude thereto.

In short, when the modulating voltage applied to grid 13 is a maximum negative value, tube 10 is virtually inoperative, no plate current flows, and the magnitude and phase of the voltage developed across coil 18 is wholly dependent upon the

carrier-frequency input voltage and the parameters of the capacitance-inductance voltage-divider network.

At a maximum positive value of modulating voltage, the mutual conductance G_m of tube 10 becomes maximum, a large carrier-frequency plate current flows through cathode-coupled coil 18, and the circuit of Figure 1 functions as a cathode-follower circuit, as will become clear from the following consideration. When the G_m of tube 10 is very high, the large carrier-frequency plate current flowing through coil 18 develops a voltage thereacross which is in phase with the carrier-frequency input voltage. This in-phase voltage opposes the input voltage and has the effect of increasing to a relatively high value the effective input impedance of the phase-modulator as seen by the applied carrier-frequency input voltage. The effect of this high input impedance is to limit the input current to a very small magnitude, and hence but a very small input current flows through capacitor 19 and coil 18. The total voltage developed across coil 18 is therefore determined almost entirely by the relatively large carrier-frequency plate current flowing therethrough.

In brief, when the modulating signal is strongly positive, the circuit of Figure 1 resembles a cathode-follower circuit and has the well-known characteristics thereof, namely, the input impedance is very high, the output voltage developed across the cathode load is in phase with the input voltage, and the magnitude of the output voltage is almost equal to that of the input voltage, being just slightly smaller.

In summary of the foregoing, assuming the inductive reactance of coil 18 at the operating carrier frequency to be smaller than that of the grid-to-cathode capacitive reactance, my novel circuit arrangement is effective to accomplish the following: At maximum negative modulating signal voltage, the G_m of tube 10 is substantially zero and the voltage developed across coil 18 is 180° out of phase with the input carrier-frequency voltage. At maximum positive signal voltage, the G_m of tube 10 is very large and the voltage developed across coil 18 is substantially in phase with the input voltage. For modulating voltages intermediate these two extremes, the G_m of tube 10 assumes instantaneous intermediate values which are a non-linear function of the applied modulating voltages, and the instantaneous voltage developed across coil 18 is out of phase with the input carrier-frequency voltage by an amount which is dependent upon the instantaneous G_m of the tube.

If the grid-to-cathode capacitive reactance of tube 10 be twice as large as the inductive reactance of coil 18, then in addition to the above recited phase relationships, the output voltage and input voltage will be substantially equal in magnitude at all times irrespective of the instantaneous value of modulating voltage applied to grid 13. The constancy of the relationship between the magnitudes of the input and output voltages may be explained by the fact that the current through coil 18 is comprised of two components which are out of phase and differentially related in magnitude. That is to say, as the applied modulating signal increases in a positive direction, the mutual conductance of the tube increases and so does the plate current component of the current through coil 18. But the voltage thus developed across coil 18 opposes the input voltage; and the input impedance

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of the phase-modulator consequently increases as a function of the developed voltage. The increase in input impedance decreases the input component of the total current through coil 18, and offsets the increase in the plate-current component. The net result is that the voltage developed across coil 18 remains substantially constant in magnitude, i. e., equal at all times to the applied input voltage. The phase, however, changes.

With respect now to the linearity of the phase variations, it is to be understood that linearity is dependent upon the grid-volts versus mutual-conductance characteristic of the particular tube and upon the value of the reactance of the cathode-coupled coil 18. For a given tube, and a selected value of cathode-load reactance, the degrees of phase-shift may be readily calculated and plotted for various linearly-spaced values of grid volts. A convenient formula for this purpose is

$$\tan \theta = \frac{4G_m X_k}{4G_m^2 X_k^2 - 1}$$

where

θ = Degrees phase shift.

X_k = Cathode load reactance.

G_m = Mutual conductance of tube for the various values of grid volts.

The above formula assumes that the amplification factor of the tube is very much greater than one and that the cathode load reactance is one-half the grid-to-cathode capacitive reactance. It will be evident that by plotting a series of graphs for various values of cathode-load reactance X_k for each of various tubes, determination may be made of the combinations of tube and cathode load reactance which give the more linear phase-shift characteristics.

In the operation of my novel phase modulator as described above, it is assumed that the magnitude of the carrier-frequency input signal is insufficient to cause substantial variations in the G_m of tube 10. Incidentally, one of the advantages of using a variable- μ tube is that the root-mean-square value of the carrier-frequency input signal may be larger without introducing undesirable variations in the G_m of the tube. Another advantage is that the operation of the phase modulator is less critical with respect to the constancy of the fixed potentials applied to the electrodes. These advantages flow from the fact that the grid-volts versus degrees-phase-shift characteristic of a variable- μ tube is less steep than that of sharper cut-off tubes.

Referring again to Figure 1, attention is called to the fact that while capacitor 19 has thus far been described as being present in the circuit between the grid and cathode electrodes of tube 10, there may be instances in which capacitor 19 may be omitted altogether, as for example, where the operating carrier frequency is very high and the capacitive reactance between grid and cathode due to the inter-electrode capacitance is adequate for the purpose.

In Figure 2 there is shown an illustrative grid-volts versus degrees-phase-shift characteristic of the circuit of Figure 1. It will be observed that linear phase modulation is not obtained over the entire 180° range, slight distortion occurring at the two extremes of the curve. Linear phase shift is obtained, however, over a range of about 140°. My improved circuit consequently permits phase modulation of the order of plus and minus

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70° prior to frequency multiplication. This, to the best of my knowledge, is substantially greater than that achieved by prior art systems without the use of special and expensive apparatus.

Results similar to those obtained from the circuit shown in Figure 1 are obtainable from the modified circuit shown in Figure 3, in which many of the elements are identical to those of Figure 1 and are identified by the same reference numerals. In the circuit of Figure 3, however, the cathode-coupled load coil is replaced with a cathode-coupled load capacitor 44 across which the output voltage is developed. Coil 43 is a carrier-frequency choke. An inductance coil 40 is connected between grid 13 and cathode 12. Capacitor 42, shown in series with coil 40, is a blocking capacitor having low impedance to radio frequencies but high impedance to modulating frequencies. The reactance of coil 40 at operating carrier frequency is larger than that of capacitor 44, preferably twice as large in order to keep simultaneous amplitude modulation to a minimum.

The circuits shown in Figures 1 and 3 may, by changing the relative values of capacitor 24 and grid resistor 22, be used to provide indirect frequency modulation. A definition and discussion of indirect frequency-modulation may be found in "Frequency Modulation" by Hund, 1942. When my circuits are employed to provide phase modulation, the reactance of capacitor 24 at the modulating frequencies should be much greater than the resistance of grid resistor 22. When, however, the circuits are to be used to provide indirect frequency modulation, the reactance of capacitor 24 at modulating frequencies should be much smaller than the resistance of resistor 22.

In describing the operation of my circuit I have assumed the input voltage to be of substantially constant high carrier frequency since in many applications of my phase modulator the signal applied to input circuit 25 will be an unmodulated radio frequency voltage. It should be understood, however, that the input voltage may be of lower than radio frequency, the requirement merely being that the modulating signal be of lower frequency, preferably substantially lower, than the frequency of the input voltage. It should be further understood that the voltage applied to input circuit 25 may be a modulated signal which is to be further modulated, and that if desired, two or more of my novel phase modulator circuits may, with suitable isolation, be coupled in tandem.

Having described my invention, I claim:

1. In a phase-modulation system; a vacuum tube having cathode, plate and grid; a source of alternating input voltage of predetermined frequency connected between said grid and a point of reference potential; a source of direct-current plate voltage connected between said plate and said point; a first reactance, having substantial magnitude at the frequency of said input voltage, connected between said cathode and said point, said first reactance being common to the grid-cathode and plate-cathode circuits of said tube; a second reactance of opposite sign connected directly between said grid and said cathode, the magnitude of said second reactance at the frequency of said input voltage being substantially larger than that of said first reactance; modulating means connected in the grid-cathode circuit of said tube for varying the tube's mutual conductance at a frequency lower than the frequency of said input voltage; and means for deriving an output voltage between said cathode and said point.
2. In a phase-modulation system; a vacuum

tube having cathode, plate and grid; a source of alternating input voltage of substantially constant peak amplitude and frequency connected between said grid and a point of reference potential; a source of direct-current plate voltage connected between said plate and said point; a reactance, having substantial magnitude at the frequency of said input voltage, connected between said cathode and said point, said reactance being common to the grid-cathode and plate-cathode circuits of said tube; a reactance of opposite sign obtaining between said grid and said cathode, the magnitude of said last-mentioned reactance at the frequency of said input voltage being substantially twice that of said first-mentioned reactance; modulating means connected in the grid-cathode circuit of said tube for varying the tube's mutual conductance at a frequency lower than the frequency of said input voltage; and means for deriving an output voltage between said cathode and said point.

3. The combination claimed in claim 2 characterized in that said first-mentioned reactance is an inductance.

4. In a phase-modulation system; a vacuum tube having cathode, plate and grid; a source of alternating input voltage of substantially constant frequency connected between said grid and a point of fixed potential; a source of direct-current plate voltage connected between said plate and said point; a first reactance, having substantial magnitude at the frequency of said input voltage, connected between said cathode and said point, said first reactance being common to the grid-cathode and plate-cathode circuits of said tube; a second reactance of opposite sign connected directly between said grid and said cathode, the magnitude of said second reactance at the frequency of said input voltage being substantially larger than that of said first reactance; means for applying a fixed bias to said tube; means for applying a modulating signal between said grid and cathode, the frequency of said modulating signal being lower than the frequency of said input voltage; and means for deriving an output voltage between said cathode and said point of fixed potential.

5. In a phase-modulation system; a vacuum tube having cathode, plate and grid; a source of alternating input voltage of substantially constant frequency connected between said grid and a point of fixed potential; a source of direct-current plate voltage connected between said plate and said point; a first reactance, having substantial magnitude at the frequency of said input voltage, connected between said cathode and said point, said first reactance being common to the grid-cathode and plate-cathode circuits of said tube; a second reactance of opposite sign connected directly between said grid and said cathode, the magnitude of said second reactance at the frequency of said input voltage being substantially twice that of said first reactance; means for applying a fixed bias to said tube; means for applying a modulating signal between said grid and cathode, the frequency of said modulating

signal being lower than the frequency of said input voltage; and means for deriving an output voltage between said cathode and said point of fixed potential.

6. The combination claimed in claim 5 characterized in that said plate is coupled to said point of fixed potential by means having substantially negligible impedance at the frequency of said input voltage.

7. In a phase-modulation system; a vacuum tube having cathode, grid and plate; a source of voltage of substantially constant carrier frequency connected between said grid and ground; a source of direct-current voltage connected between said plate and ground; an inductive reactance connected between said cathode and ground, said inductive reactance being common to the grid-cathode and plate-cathode circuits of said tube, the magnitude of said inductive reactance at said carrier frequency being substantial and of the order of one-half the magnitude of the capacitive reactance obtaining between said grid and cathode; modulating means connected in the grid-cathode circuit of said tube for varying the tube's mutual conductance; and means for deriving an output voltage between said cathode and ground.

8. In a phase-modulation system; a vacuum tube having cathode, anode and grid; a source of voltage of predetermined radio frequency connected between said grid and a point of fixed potential; a source of direct-current voltage connected between said anode and said point; a first reactance, whose magnitude at said radio frequency is substantial, connected between said cathode and said point, said first reactance being common to the grid-cathode and plate-cathode circuits of said tube; a second reactance of opposite sign connected directly between said grid and cathode, the magnitude of said second reactance at said radio frequency being of the order of twice that of said first reactance; a source of fixed biasing voltage connected in the grid-cathode circuit of said tube, said biasing voltage being of such magnitude as to produce operation of said tube on the non-linear portion of the grid-volts versus mutual-conductance characteristic; a source of modulating signal connected in the grid-cathode circuit of said tube; and means for deriving a radio-frequency output voltage between said cathode and said point of fixed potential.

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