

July 8, 1941.

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2,248,239

PHASE SHIFTING NETWORK

Filed Aug. 15, 1938.

2 Sheets-Sheet 1

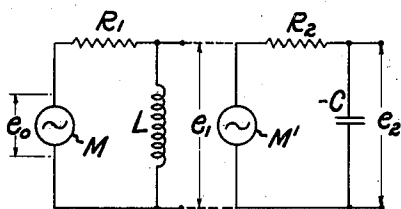


Fig. 1.

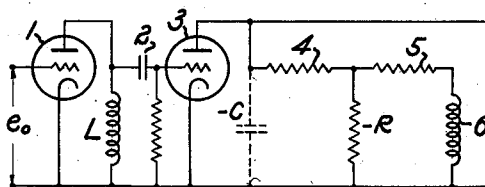


Fig. 2.

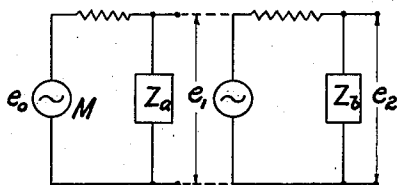


Fig. 3.

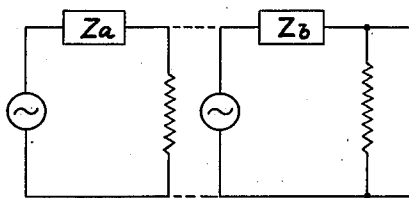


Fig. 4.

Z_a	Z_b
$+L$	$-C$
$-L$	$+C$
$-C$	$+L$
$+C$	$-L$

Fig. 5.

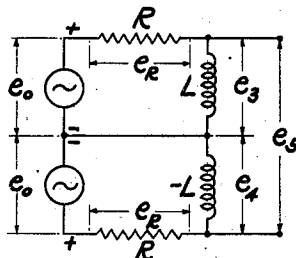


Fig. 6.

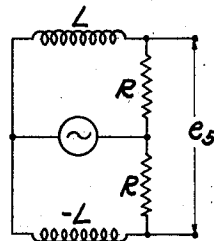


Fig. 7.

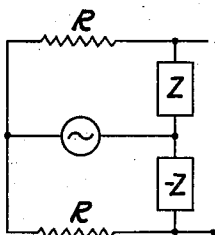


Fig. 8.

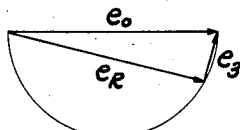


Fig. 9.

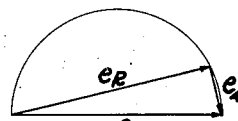


Fig. 10.

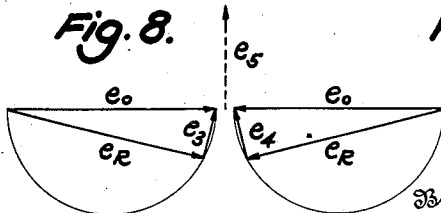


Fig. 11.

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Fig. 12.

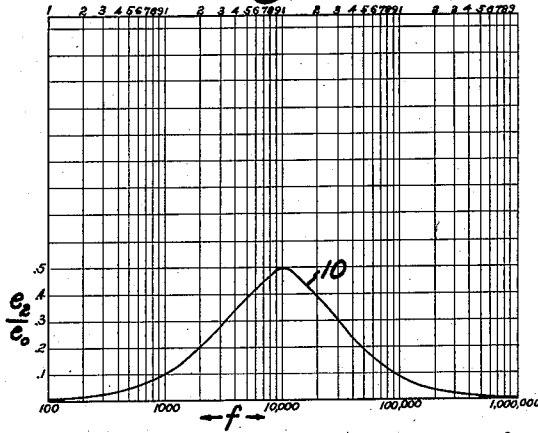


Fig. 13.

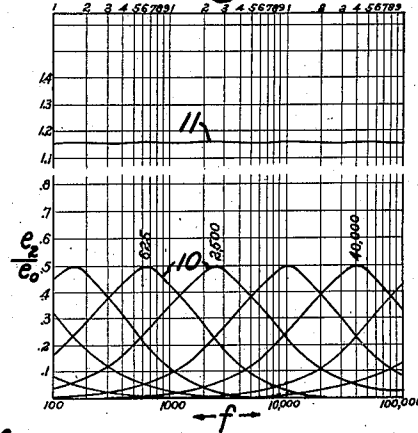


Fig. 14.

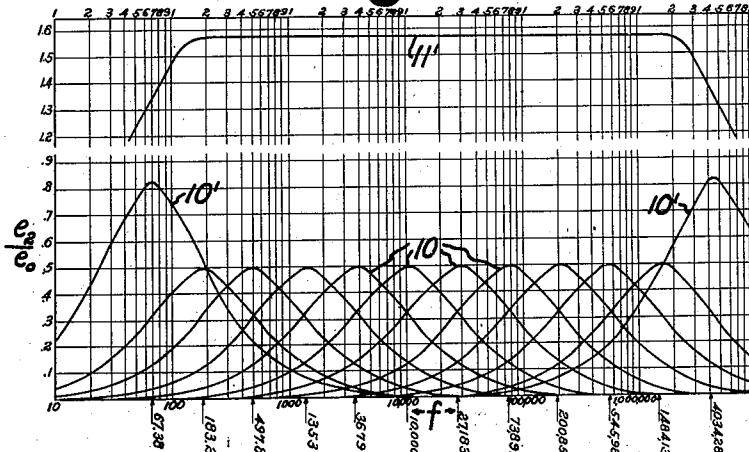
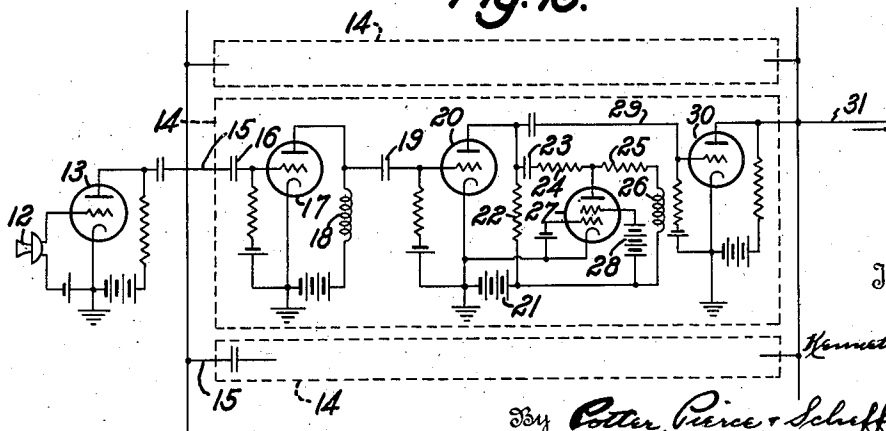


Fig. 15.



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PHASE SHIFTING NETWORK

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Application August 15, 1938, Serial No. 225,021

13 Claims. (Cl. 173-44)

This invention relates to phase shifting networks and particularly to methods of and circuit arrangements for the transmission of signal frequency voltages with a phase shift of exactly 90° .

A proposed method for the production of a radiated signal of the single sideband characteristic was predicated upon the cancellation of one sideband by combining two simultaneously produced modulated carriers, one carrier voltage and the modulating voltage thereon being displaced exactly 90° from the other carrier and its modulating voltage. The method was theoretically sound and no difficulty was experienced in effecting the desired phase shift of one carrier component. The problem of effecting a phase shift of the modulating voltage was more difficult and, so far as I am aware, there has been no entirely satisfactory method for obtaining a phase shift of 90° , at constant amplitude, over the wide band of audio frequency voltages. The band of modulation frequencies for television is much wider and the known phase shifting circuits would have resulted in wide variations of phase displacement and of amplitude with frequency.

An object of this invention is to provide improved methods of and circuits for obtaining a phase shift of 90° in the transmission of signal frequency voltages. An object is to provide methods of and circuit arrangements for obtaining a frequency-independent transmission, with a phase shift of exactly 90° , of a band of signal frequency voltages, the method and circuits being characterized by the use of a plurality of phase shifting networks which each have a transmission efficiency that varies with frequency. Further objects are to provide phase shifting methods and circuits that combine the phase shifts of a positive and of a negative reactance. Other objects are to provide phase shifting circuits of the type last stated in which the reactances are of the same or of different character; that is, one an inductance and the other a capacitance, or both either an inductance or a capacitance.

These and other objects and advantages of the invention will be apparent from the following specification when taken with the accompanying drawings, in which:

Fig. 1 is a schematic diagram of a circuit for producing a phase shift;

Fig. 2 is a diagram of a circuit having the characteristics of the Fig. 1 diagram;

Figs. 3 and 4 are generalized schematic dia-

grams of phase shifting networks that include positive and negative reactances in series;

Fig. 5 is a tabulation of the several reactance combinations that may be used in Figs. 3 and 4 circuits;

Figs. 6 and 7 are circuit diagrams of phase shifting networks that include positive and negative inductances in parallel;

Fig. 8 is a generalized circuit diagram of an alternative arrangement of like reactances of positive and negative characteristics;

Figs. 9 to 11, inclusive, are vector diagrams illustrative of the phase displacing action of the circuits of Figs. 6 to 8;

Fig. 12 is a curve sheet showing the typical frequency-amplitude characteristic of a single phase shifting unit;

Figs. 13 and 14 are curve sheets, showing the individual and the summation frequency-amplitude characteristics of a plurality of such units; and

Fig. 15 is a circuit diagram of a multiple unit phase shifting network embodying the invention.

A transmission network may be assembled from a number of units, each including a negative impedance, to satisfy the rigorous requirement of passing all modulating or signal frequencies with the same attenuation or amplification, and of shifting their phase by the constant amount of 90° at each individual and simultaneously applied signal frequency. The design and operating characteristic of typical individual units will be explained, and an example of one circuit embodiment will then be described.

The term "positive reactance," as used in this specification and in the claims, identifies a capacity or an inductance of conventional type, and the term "negative reactance" refers to a reactance whose phase angle is opposite to that of a reactance of the conventional type. That is, a negative capacity draws a lagging current, and a negative inductance draws a leading current.

One form of phase shifting circuit, as shown schematically in Fig. 1, comprises a generator M or source of modulation frequency voltage e_0 in series with resistance R_1 and an inductance L. The generator M and resistance R_1 may be the equivalent internal generator and internal plate resistance of a vacuum tube amplifier. The potential e_1 across the inductance L is applied to another vacuum tube which is indicated by the equivalent elements, i. e. a generator M' in series with a resistor R_2 and a negative capacity

—C. The potential e_2 across the terminals of the negative capacity 6 is displaced by exactly 90° from the potential e_0 of the generator M.

A vacuum tube circuit corresponding to the Fig. 1 diagram is shown in Fig. 2. The voltage e_0 is the input to a vacuum tube amplifier 1 having a plate load L that is coupled through the condenser 2 to the vacuum tube 3. The plate load of the tube 3 is a network that has the impedance characteristic of the negative capacity —C. This network comprises the series resistances 4, 5, the negative resistance —R connected between the junction of the resistances and ground, and the inductance 6 connected from the outer terminal of resistance 5 to ground. The negative resistance —R may be provided by a dynatron, a feedback amplifier or by other known negative resistance devices. Networks of this general type are known for creating a negative capacity equal to:

$$C = \frac{-R^2}{L}$$

where L is the value of the inductance 6.

As stated above, the phase of the voltage e_2 across the capacity —C is displaced by exactly 90° from the source voltage e_0 . Assuming, for simplicity of explanation, that R_1 and R_2 are equal, and have the value R, and that the amplification constants μ_1 , μ_2 of tubes 1, 3 respectively, are each equal to unity, the voltage relationships in the circuits of Figs. 1 and 2 may be computed as follows:

$$e_1 = e_0 \frac{j\omega L}{R + j\omega L} \quad (1)$$

$$e_2 = e_1 \frac{j\frac{1}{\omega C}}{R + j\frac{1}{\omega C}} \quad (2)$$

Substituting the value of e_1 in Equation 2 and, assuming that the circuit design is such that

$$R^2 = \frac{L}{C} \quad (3)$$

the voltage e_2 across the negative capacity is:

$$e_2 = j e_0 \frac{R}{\omega L + \frac{1}{\omega C}} \quad (4)$$

If the amplification factors of the tubes are not unity, this equation becomes:

$$e_2 = j e_0 \left[\frac{R}{\omega L + \frac{1}{\omega C}} \right] \mu_1 \mu_2 \quad (5)$$

Equations 4 and 5 show that the voltage e_2 across the negative capacity —C is at 90° with respect to the input voltage e_0 regardless of frequency.

When R_1 and R_2 are different, the value of e_2 may be computed as:

$$e_2 = j e_0 \frac{\frac{L}{C}}{j \left(\frac{L}{C} - R_1 R_2 \right) + \left(R_2 \omega L + \frac{R_1}{\omega C} \right)} \quad (6)$$

If, by design,

$$R_1 R_2 = \frac{L}{C}$$

and

$$\frac{R_1}{\omega_0 L} = \frac{R_2}{\frac{1}{\omega_0 C}} \quad (7)$$

which results in equal phase angles at the fre-

quency ω_0 of maximum transmission, Equation 6 reduces to

$$e_2 = j e_0 \frac{R_1}{\omega_0 L \left(n + \frac{1}{n} \right)} \quad (8)$$

where n is a variable and $\omega = n\omega_0$.

It is to be noted that this equation is of the same form as Equations 4 and 5, thus indicating that the phase shift of the network is not dependent upon an equality of the resistances of the two sections.

The fact that the phase shift is of the order of 90° for all frequencies may be ascertained from an inspection of the Fig. 1 circuit. At very low frequencies, the voltage e_1 across the inductance L leads the source voltage e_0 by almost 90° , and the voltage across the negative capacity —C is almost in phase with its input voltage e_1 . The overall phase shift is therefore 90° at low frequencies. As the frequency increases the phase shift in the voltage e_1 across inductance L decreases but the phase shift in the negative capacity circuit increases correspondingly, and the sum of the phase shifts remains constant.

Unfortunately, the amplitude of the voltage e_2 across the negative capacity is not independent of frequency. This frequency-amplitude variation can be corrected and appropriate corrective means will be described after an explanation of other phase shifting units.

The network of Fig. 1 is a specific arrangement of a generalized circuit, Fig. 3, in which impedances Z_a , Z_b are shown in place of the inductance L and capacity —C of Fig. 1. The tabulation of Fig. 5 indicates the several possible combinations of unlike impedances of positive and negative character.

The general circuit arrangement of reactive impedances in series with shunt resistances is shown in Fig. 4. It can be demonstrated mathematically that the Fig. 4 circuit has the same phase shifting characteristics as the series resistance, shunt reactance circuit of Fig. 3. Appropriate combinations of unlike reactances for the Fig. 4 circuit are shown in tabulation of Fig. 5.

The desired phase shift of exactly 90° may also be obtained with positive and negative impedances of like character; the impedances being located in parallel circuits which produce equal phase shifts of opposite sign when equal voltages of opposite phase are impressed upon the circuits. As shown schematically in Fig. 6, the two parallel circuits each include a source of voltage e_0 , a resistance R and an impedance, one impedance being a positive inductance L and the other a negative inductance —L. The input voltages are of opposite phase and develop voltages e_R across the resistances R, voltages e_3 , e_4 across the +L and —L, respectively; these voltages being combined across output terminals connected to the outer ends of the inductances to provide output voltage e_5 .

It is apparent that, for applied voltage e_0 of the same phase, the phase shift in the two circuits will be in opposite directions since the reactance of one circuit is positive while that of the other is negative. The vector diagrams of Figs. 9 and 10 show this relationship for the illustrated case of inductive reactances, and also show that the lagging and leading phase angles α will be equal when the resistances R are equal and the inductances have the same numerical value. But the input voltages e_0 of the parallel branches are

out of phase and one of the vector diagrams is reversed, as shown in Fig. 11. Since e_3 and e_4 are equal and are displaced by the same amount from the applied voltages, the resultant e_5 of the summation of the voltages e_3 and e_4 is always at 90° to the applied voltages.

The described phase shifting units supply the desired phase shift of exactly 90° but the amplitude of the output voltage varies with frequency. Examination of Equation 4 indicates that the output voltage e_2 is zero for zero frequency and for infinite frequency, and that it rises to a peak value of $0.5 e_0$ at the frequency at which

$$\omega L = \frac{1}{\omega C} = R$$

Amplification by the tubes will raise the output voltage, as indicated by Equation 5 but the fundamental operation is not affected by amplification and, for simplicity, it will be assumed that the amplification is unity. The transmission or frequency-amplitude characteristic of a single unit, as shown by curve 10 of Fig. 12, is symmetrical about a vertical axis passing through the peak value when plotted on a logarithmic frequency scale.

An almost infinite number of such transmission characteristics, with maximum transmission peaks spaced from each other by only a few cycles, will give a flat summation characteristic corresponding to a uniform transmission at all frequencies. The sum e_T of the voltages of a plurality of units that have voltage peaks spaced from each other, in frequency, by a constant multiplier S , is

$$e_T = e_0 \sum_{p=-\infty}^{p=+\infty} \frac{f f_0 S^p}{f^2 + f_0^2 S^{2p}} \quad (9)$$

where f is the frequency at which the voltages are to be added, f_0 is the frequency of the peak voltage of the single unit, and p is an integer from minus infinity to plus infinity corresponding to the voltage contributed by the minus or the plus p circuit below or above the reference frequency f_0 . Calculation and experiment show that when S is the base of the hyperbolic logarithms, i. e. 2.7182818, the summation voltage e_T is a constant value that is independent of f . A spacing of the peak voltage frequencies of the separate phase shifting units by $S=2.7182818$ will provide the constant phase of 90° and all frequencies will be transmitted with equal efficiency, the output voltage e_T being approximately 1.5705 e_0 .

A different spacing of the peak frequencies of successive units will introduce a frequency-amplitude error but the frequency spacing is not extremely critical and the factor S may depart materially from its optimum value without introducing large errors. The summation voltage of units having peaks spaced by one octave, i. e. $S=2$, will be constant within about 1% of the mean value, and a network having units designed for voltage peaks spaced by $S=4$ will maintain the summation voltage constant within $\pm 0.5\%$ at all frequencies.

The transmission characteristics of a network of the $S=4$ type are shown in Fig. 13. The several phase shifting units are in parallel in the transmission path and have individual frequency-amplitude characteristics represented by the overlapping curves 10. These curves rise to a maximum at the frequencies 156.25, 625, 2500, 10,000, etc., and, for a network of this $S=4$ type, the curve 11 of the summation voltage e_T has a

practically constant amplitude of 1.130 e_0 . The amplitude error of $\pm 0.5\%$ will be immaterial in most instances. A further reduction of the number of units by increasing S to 10 will introduce a maximum error of about 5% ($\pm 5.47\%$) for a mean value of e_T of about 0.68 e_0 .

The curves of Fig. 14 were plotted for a network having a finite number of units for effecting a frequency-independent phase shift within a finite range of frequencies. The peaks of the component units are spaced by the ideal value of $S=2.7182818$ and the peak frequencies of the several units are noted on the curve sheet. All of the intermediate units have the same transmission efficiency, as indicated by the similar curves 10, but the end units have an approximately 65% higher efficiency as shown by curves 10'. The constant amplitude section of the summation voltage curve 11' therefore extends well beyond the limits that would be obtained if all units had the same transmission efficiency. The number of units required for a given frequency range is thus reduced as the end sections compensate to some extent for the voltage contributions of the adjacent omitted units.

Curve 11' is flat between about 150 cycles and 2 megacycles, and this wide frequency range of constant amplitude transmission is obtained with but twelve phase shifting units. Inspection of the curve sheet shows that only seven units would be required to cover the range of from 150 cycles to 10 kilocycles if the unit which is peaked at 27,183 cycles is made the end unit of higher transmission efficiency. A lesser number of units will be required if some amplitude error can be tolerated and, for other spacings of the peak voltages, the increased transmission of the end units should be adjusted to provide the greatest range of approximately constant transmission.

A fragmentary circuit diagram for a network assembly of units of the Fig. 1 type is shown in Fig. 15. The source of signal voltage is the microphone 12 and its amplifier 13 to which a plurality of phase shifting units, indicated generally by the dotted line blocks 14, are connected in parallel. The number of units 14 will depend upon the range of modulation frequencies and the permissible amplitude error. The circuit on only one unit is shown as the units are of identical design but have impedances of different values. The output voltage of amplifier 13 passes by lead 15 and blocking condenser 16 to the grid of vacuum tube 17 which has an inductive plate load 18 that corresponds to the positive inductance L of Fig. 1. The voltage developed across inductance 18 is passed by condenser 19 to the grid of the vacuum tube 20. The plate voltage to tube 20 is from a current source 21 through a resistor 22 in parallel with the plate load that provides the negative capacity $-C$ of Fig. 1. The current sources for energizing the tubes are shown, for simplicity, as batteries but the customary energization from an alternating current source and rectifiers will usually be employed.

The negative capacity network is connected to the plate of tube 20 through an isolating condenser 23 and comprises the serially connected resistors 24, 25 and inductance 26, and the dynatron tube 27 that has a plate connected to the junction of resistors 24, 25 and a cathode connected to the cathode of tube 20. The plate of the dynatron tube is energized from current source 21 through the inductance 26 and resistor 25. The screen grid of tube 27 is connected through a battery 28 to the positive terminal of

the battery 21, the polarity of the battery 28 being such that the screen grid has a higher positive potential than the plate. The dynatron tube 20 functions as a negative resistance device and, in the illustrated circuit, the dynatron and its plate circuit load create the effect of a negative capacity in the plate circuit of the tube 20.

The output lead 29 from the tube 20 of each unit extends to an amplifier 30, and the several amplifiers 30 work into a common output lead 31. The purpose of the amplifier tubes is to prevent coupling between the several negative capacities and thus make each unit per se independent.

The illustrated circuit places all units in parallel in the transmission path but other arrangements may be used to develop in the output lead a voltage that is the summation of the voltages developed by the several units.

The dynatron tube and other negative resistance devices have a constant resistance for only a limited range of voltages and the input to the phase shifting units should be restricted to the voltage range for which the negative resistance of the tube 27 is constant or substantially constant. The phase-shifted voltage from the plurality of units 14 may then be brought to any desired level by amplifiers individual to the units or by a common amplifier.

The design of vacuum tube circuits for producing the other described types of phase shifting units will be obvious to those familiar with negative impedance circuits. The number of units and the frequency spacing of the peak transmission may be varied in accordance with the range of frequencies to be transmitted and the allowable amplitude error. Some amplitude deficiency may be corrected in a succeeding portion of the transmission system, and this possibility of course increases the latitude in the design of a phase shifting network for any given use.

I claim:

1. In the transmission of signal voltages in a band of frequencies, the process of obtaining a frequency-independent phase shift of constant magnitude throughout the band which comprises impressing the signal voltages on two circuits containing reactances of opposite character and of opposite algebraic sign, thereby to produce two voltage components with phase shifts that each vary with frequency and at the same rate, and combining the two phase-shifted voltage components to produce an output voltage having a phase shift of constant magnitude.

2. In the transmission of signal voltages in a band of frequencies, the process of effecting a phase shift of exactly 90° at all frequencies which comprises impressing the signal voltages on two circuits containing reactances of opposite character and of opposite algebraic sign, thereby to produce in succession during transmission two phase shifts that vary with frequency in opposite sense and that equal 90° at respectively substantially zero and substantially infinite frequency, and adding the frequency-variant phase shifts to produce a frequency-independent phase shift of 90°.

3. In the transmission of signal voltages in a band of frequencies, the process which comprises producing from the signal voltages two voltage components of equal magnitude and with frequency-variant phase shifts of equal magnitude and opposite algebraic sign, and adding the

voltage components to obtain an output voltage of exactly 90° phase shift at all frequencies.

4. In the transmission of signal voltages in a band of frequencies, the process which comprises producing from the signal voltage a plurality of voltage components each at 90° to the signal voltage and each varying in amplitude as the signal voltage frequency departs from a maximum transmission frequency for each component, the maximum transmission frequencies for the respective components being spaced from each other, and combining the several voltage components to obtain a 90° phase shifted output voltage that is of substantially constant amplitude throughout the frequency band.

5. A phase shifting network having a frequency-independent phase shift of exactly 90°, said network comprising a transmission section having a positive reactance, a transmission section having a negative reactance, and connections between said transmission sections for combining the phase shifted output voltages of both transmission sections to produce an overall output voltage of 90° phase shift.

6. A phase shifting network having a frequency-independent phase shift of exactly 90°, said network comprising two serially arranged transmission sections each including resistance and a reactance, the reactances being of opposite character and of opposite algebraic sign.

7. A phase shifting network as claimed in claim 6, wherein both sections have the same ratio of resistance to reactance.

8. A phase shifting network comprising two transmission sections in parallel, a voltage source for impressing signal voltages of opposite phase upon said sections, each section including resistance and reactances of like character, one reactance being positive and the other negative, a pair of output terminals for the network, and circuit connections between said terminals and said sections for developing between said terminals the summation of the phase-shifted voltages of the sections.

9. A phase shifting network comprising a plurality of phase-shifting units, each unit including reactances of opposite algebraic sign and resistance for producing a frequency-independent phase shift of 90°, said reactances imparting a frequency-variant transmission efficiency to said units, a source for impressing upon said units a band of signal frequency voltages, and output terminals across which the summation of the output voltages of the several units is developed, the impedances of the several units having values corresponding to maximum transmission efficiencies at frequencies that for all pairs of adjacent units bear a substantially constant ratio.

10. In a transmission network, a plurality of circuit units, and input and output terminals between which said units are connected in parallel; each unit including reactance imparting thereto a transmission efficiency that varies with frequency as a function of

$$\frac{1}{n + \frac{1}{n}}$$

where n is a variable equal to the ratio of the frequency of maximum transmission efficiency to any other frequency for which the transmission efficiency is to be determined, and the reactances of each unit corresponding to a frequency of maximum transmission efficiency differing from the maximum transmission frequency of all other

units, the frequencies of all pairs of adjacent maximum transmission peaks having substantially the same ratio.

11. In a transmission network, the invention as claimed in claim 10, wherein the ratio of the frequencies of any two adjacent maximum transmission peaks is between 2 and 10.

12. In a transmission network, the invention as claimed in claim 10, wherein the ratio of the frequencies of any two adjacent maximum transmission peaks is substantially 2.7182818.

13. In a transmission system, input and output terminals, a plurality of transmission units in parallel between said terminals, each unit including a pair of sections having reactances of opposite algebraic sign for producing a 90° phase shift, said reactances imparting to the units a sharply-peaked frequency-variant transmission

efficiency with the maximum transmission of the several units at different frequencies to provide an approximately constant summation output, the peak transmission efficiencies of all of said units being substantially equal, and means precluding a gradual decrease in transmission efficiency in the frequency regions outside the maximum transmission efficiencies of the end units; said means comprising additional units of higher maximum transmission efficiency than said plurality of units, said additional units being connected between said terminals and having reactances imparting thereto frequencies of maximum transmission efficiency lying outside of the range of approximately constant summation output of said plurality of units.

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