Sept. 13, 1927. 1,642,389

T. E. SHEA

VOLTAGE AMPLIFIER

Filed Oct. 18, 1923 2 Sheets-Sheet 1

Fig. 1.

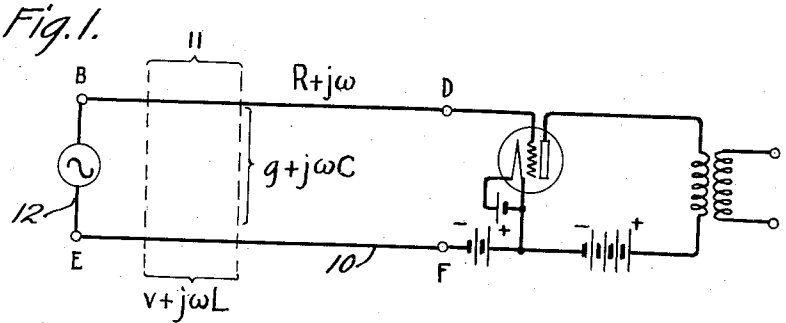


Fig. 2.

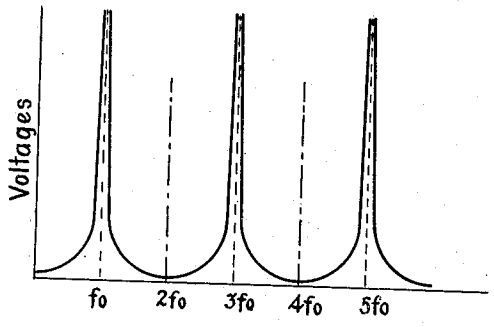


Fig. 3.

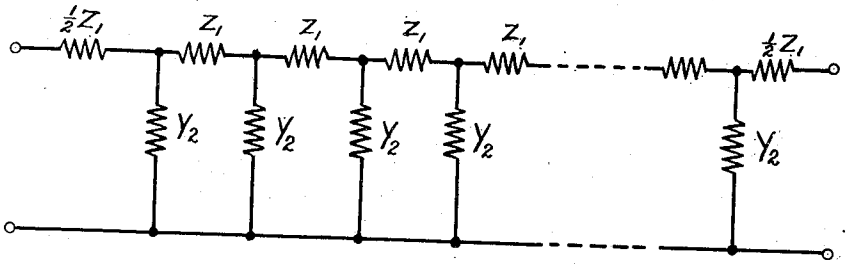
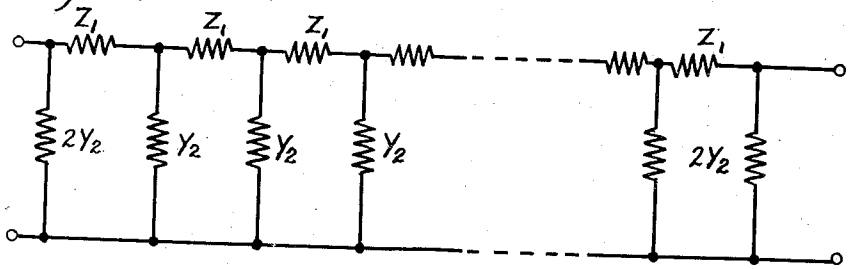


Fig. 4.



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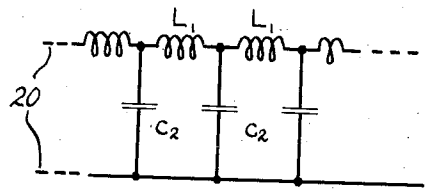
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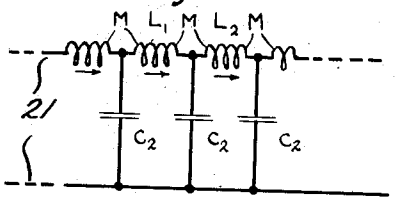
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Fig. 5.



$\theta' = \sqrt{Z_1 Y_2} = j\omega\sqrt{L_1 C_1}$; $Z = j\omega L_1$; $Y_2 = j\omega C_2$

Fig. 6.



$\theta' = \sqrt{Z_1 Y_2}$; $Z = j\omega(L_1 + 2M)$; $Y_2 = j\frac{\omega C}{1+\omega^2 MC}$

Fig. 5a

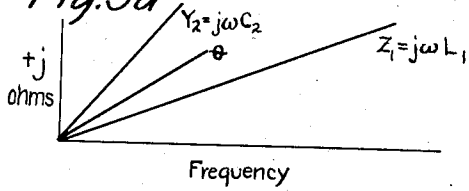


Fig. 6a

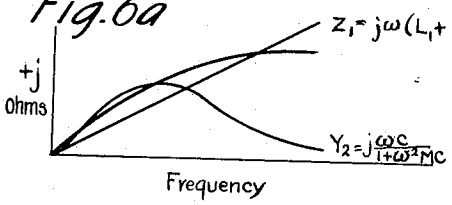


Fig 5b

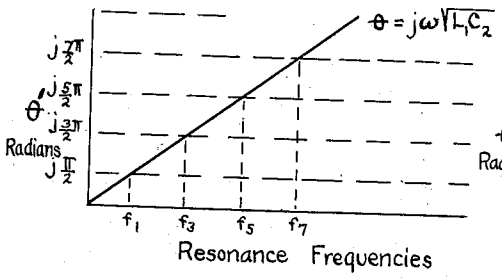


Fig 6b

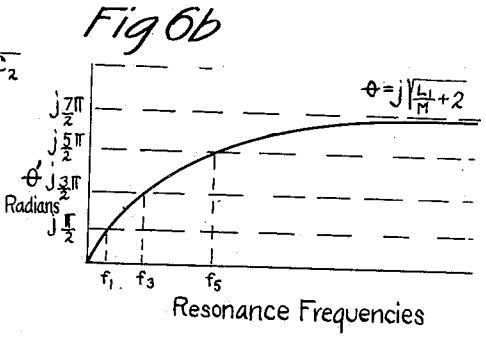


Fig. 7.

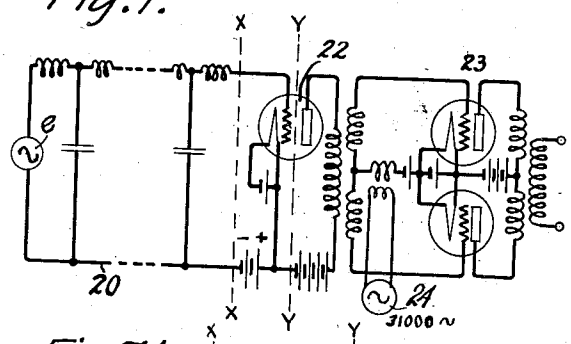


Fig. 7A.

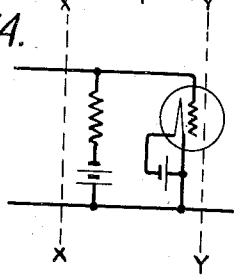
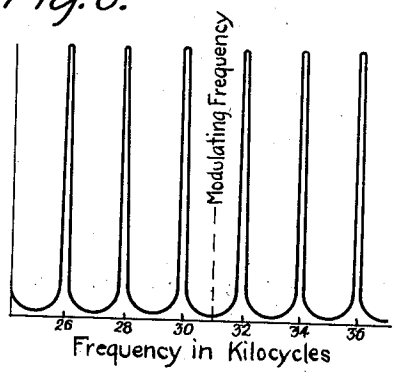


Fig. 8.



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Patented Sept. 13, 1927. 1,642,389

UNITED STATES PATENT OFFICE.

TIMOTHY E. SHEA, OF RUTHERFORD, NEW JERSEY, ASSIGNOR TO WESTERN ELECTRIC COMPANY, INCORPORATED, OF NEW YORK, N. Y., A CORPORATION OF NEW YORK.

VOLTAGE AMPLIFIER.

Application filed October 18, 1923. Serial No. 669,219.

This invention relates to the production of high voltages of certain selected frequencies by means of uniform or artificial resonating lines. Artificial lines may be defined as recurrent series of identical sections each section having lumped impedance effectively in series with the line and lumped admittance effectively in shunt across the line.

Such an artificial line tends to simulate in its electrical action a uniform line of distributed constants, the total series impedance of the uniform line being equal to the total series impedance of the artificial line and the total shunt admittance of the uniform line being equal to the total shunt admittance of the artificial line at all frequencies. The electrical angle subtended by a uniform line of distributed constants is

$$\Theta = \sqrt{Z_1 Y_2} \quad (1)$$

hyperbolic radians where Z_1 and Y_2 are the total series impedance and the total shunt admittance of the line. The correction factor which must be applied to the electrical angle of a uniform line in order to obtain the electrical angle subtended by the artificial line is:

$$K = \frac{\sinh^{-1}\frac{\theta}{2m}}{\frac{\theta}{2m}} \quad (2)$$

where m is the number of recurrent sections in the artificial line. For the derivation of this expression reference is made to Kennelly, Artificial Electric Lines, copyright 1917, and particularly to Equation No. 244, Chapter VI.

When a voltage is applied through a very small impedance at one end of a uniform line the voltage produced at the remote end, if the remote end is terminated in an infinite impedance will be:—

$$V_2 = V_1 \operatorname{sech} \Theta \quad (3)$$

where V_1 is the applied voltage and V_2 is the voltage at the remote end. The relationship expressed by Equation 3 is well known, (see for example Fleming, the Propagation of Electric Currents in Telephone and Telegraph Conductors, Chapter III, Equation 34) and in its derivation it is customary to assume that the whole E. M. F. of the source is applied to the line terminals regardless of the current strength. In other words it is assumed that there is no loss of potential in any impedance external to the line, or that the sending end terminals are virtually short-circuited.

Since

$$\operatorname{sech} \Theta = \infty, \text{ when}$$

$$\Theta = j\frac{n\Pi}{2} \quad (n \text{ being any odd integer})$$

the voltage at the far end of the line will be very large with respect to the applied voltage. There thus results a large voltage amplification which will be limited only by the effective resistance and conductance of the line but if these are reasonably small the amplification may be made large.

The artificial line will simulate a smooth line in producing such voltage amplifications except that the calculated frequencies at which the voltage amplifications occur must be corrected by applying to the electrical angle of the smooth line the correction factor given in Equation (2).

The correction factor may be controlled by m, the number of recurrent sections in the line, and may be made of the order desired by using the proper number of sections.

In order that

$$\Theta = j\frac{n\Pi}{2}$$

in either uniform or sectional lines it is necessary that in certain frequency ranges the series impedance be substantially inductive reactance and the shunt admittance be substantially capacitative susceptance, or vice versa, that the series impedance be substantially capacitative reactance and the shunt admittance be substantially inductive susceptance. The angle subtended by the smooth line and the artificial line will then be respectively

$$\Theta = j\sqrt{X_1 B_1} \quad (4)$$

where X_1 is the total series reactance and B_1 the total shunt susceptance, and

$$\Theta^1 = K\Theta = jK\sqrt{X_1 B_1} \quad (5)$$

Heretofore, so far as known, no use has been made of voltages produced at the distant end of a uniform or sectional artificial line because (1) the power output is small, (2) the introduction of the impedance of ordinary translating circuits, to which the voltages would have to be transferred,

causes the disappearance of the resonance phenomena themselves, and (3) the impedance of the voltage source has not been properly designed and related to the line. In particular it may be pointed out that in the prior practical application of sectional networks, of the type under discussion as filters, it has been the usual custom to terminate the network in an impedance equal to the surge impedance of the network. Because of this the phenomenon of high voltage production at certain selected frequencies is avoided.

It is herein proposed to utilize the high voltages which may be set up by the methods hereinbefore described by employing them to control vacuum tube repeater circuits of practically infinite input impedance and since such circuits are controlled almost entirely by voltage variations rather than power variations it becomes possible to utilize what have heretofore been considered negligibly small amounts of power. It is known how to make vacuum tube input circuits of impedances of the order of 1,000,000 ohms and upward for almost any frequency over a wide range of frequencies. These values are sufficiently high to be considered practically infinite inasmuch as they disturb, to a negligible extent only, the resonance phenomena herein considered. Lower impedances may be made use of under certain conditions consequently the invention is not limited to any precise value of input impedance.

The impedance of the input circuit or voltage source through which voltages to be amplified are applied to the network may be made to have negligible effect.

(1) By making the impedance of the portion of the circuit through which the voltages are impressed on the network, small in comparison with the impedance of the network,

(2) By incorporating the impedance of the voltage-providing circuit in the structure of the line,

(3) By the insertion of an annulling impedance in series with the voltage providing circuit, or

(4) By translating the voltages to be amplified through a circuit so designed that its output impedance may be treated by (1), (2) or (3).

An object of the invention, therefore, broadly stated, is to produce greatly amplified voltages of a selected frequency or frequencies by means of uniform electrical lines or artificial lines.

In further describing the invention reference will be made to the accompanying drawings wherein Fig. 1 is a diagram of a uniform line which is used in explaining the theory of the invention; Fig. 2 is a diagram illustrating the selectivity of such a line as Fig. 1 for certain voltages; Figs. 3 and 4 are diagrams of a T-network or line and a pi-network or line respectively; Figs. 5 and 6 are diagrams of typical sectional lines with formula applicable to the design thereof; Figs. 5^a, 5^b, 6^a and 6^b are graphs explanatory of Figs. 5 and 6; Fig. 7 is a circuit diagram of a system for producing a selected series of carrier waves; Fig. 7^a a modified form of Fig. 7, and Fig. 8 a diagram illustrating the selective action of such a circuit as that of Fig. 7.

A consideration of the general theory of this invention and of the effect of series resistance and shunt conductance upon the voltages which will be set up at the distant end of the line will make clear the basic principles of operation of systems embodying the invention.

With reference to Fig. 1 the uniform line 10 has a series impedance for unit length 11 of $Z=r+j\omega L$ ohms or a total series impedance of

$$Z_1=R+j\omega L_s=l(r+j\omega L)$$

where l is the length of the line r is the resistance per unit length, L is the inductance per unit length, R is the total resistance, and L_s is the total inductance. The shunt admittance per unit length 11 is $Y=g+j\omega C$ or a total shunt admittance of

$$Y_2=G+j\omega C_s=l(g+j\omega C),$$

where g is the shunt conductance per unit length, C is the shunt capacity per unit length, and G and C_s are the total shunt conductance and capacity respectively.

A source of voltage 12 of value e is connected across the input terminals BE and a vacuum tube repeater across the output terminals DF. We will assume that the grid-filament impedance of the repeater is only negligibly different from infinity.

Then

$$\frac{V_{DF}}{V_{BE}}=T=\operatorname{sech}\Theta \quad (6)$$

T representing the ratio of voltage, V_{DF}, at the far end of the line to the voltage, V_{BE}, impressed upon the near or input end.

$$T=\operatorname{sech}(\Theta_1+j\Theta_2)=\operatorname{sech}\sqrt{(R+j\omega L_s)(G+j\omega C_s)} \quad (7)$$

$$=\operatorname{sech}\omega\sqrt{L_sC_s}\sqrt{\left(\frac{R}{\omega L_s}+jl\right)\left(\frac{G}{\omega C_s}+jl\right)}, \quad (8)$$

where Θ_1 and Θ_2 are the real and the imaginary parts of Θ. Further,

$$\Theta=l\alpha=\Theta_1+j\Theta_2=l\alpha_1+jl\alpha_2=\sqrt{(R+j\omega L_s)(G+j\omega C_s)},$$

where α=the electrical angle per unit length of the line, and α_1 and α_2 are the real and imaginary parts of α

Now let

$$\frac{\omega L_s}{R} = Q_L$$

and

$$\frac{\omega C_s}{G} = Q_c.$$

If Q_L and Q_c are large compared to unity,

$$T = \text{sech } j\omega\sqrt{L_sC_s}\left[1 - j\frac{1}{2}\left(\frac{1}{Q_L}+\frac{1}{Q_c}\right)\right], \quad (9)$$

approximately.

If $\omega\sqrt{L_sC_s} = \frac{n\Pi}{2}$, n being any odd integer, then

$$T = \text{sech}\left[\frac{n\Pi}{4}\left(\frac{1}{Q_L}+\frac{1}{Q_c}\right) + j\frac{n\Pi}{2}\right] \quad (10)$$

approximately.

But since

$$\text{sech}\left(\theta_1 + jn\frac{\Pi}{2}\right) = \mp j\,\text{csch}\,\theta_1,$$

the size of T is approximately determined by

$$T = \text{csch}\,\frac{n\Pi}{4}\left(\frac{1}{Q_L}+\frac{1}{Q_c}\right). \quad (11)$$

But since csch θ_1 approaches $\frac{1}{\theta_1}$ when θ_1 is small we have approximately,

$$T = \text{csch}\,\frac{n\Pi}{4}\left(\frac{1}{Q_L}+\frac{1}{Q_c}\right) = \frac{4}{n\Pi}\left(\frac{Q_LQ_c}{Q_L+Q_c}\right). \quad (12)$$

From the foregoing it appears that for large values of Q_L and Q_c, T becomes very great.

The behavior of T for large values of Q_L and Q_c for a line such as shown in Fig. 1, is shown in Fig. 2 in which the ratio T for each peak value of voltage has a definite finite value given by Equation (12). If R and G are constant the several peaks will be of equal amplitude. If Q_L and Q_c are constant the successive peak voltages will diminish in a ratio inversely proportional to the frequency.

Consider the action of artificial lines having lumped shunt impedances and lumped series impedances such as shown in Figs. 3 or 4, these being representative of symmetrical lines having the two generally used types of termination commonly known as mid-series and mid-shunt terminations.

The electrical angle α of such lines per section is

$$\alpha = \alpha_1 + j\alpha_2 = 2\,\sinh^{-1}\frac{1}{2}\sqrt{Z_1Y_2} \quad (13)$$

where Z_1 is the series impedance and Y_2 is the shunt admittance of each section.

For a line having m sections electrical, angle factor is

$$\theta' = m\alpha = \theta'_1 + j\theta'_2 = m\alpha'_1 + jm\alpha'_2 \quad (14)$$
$$= 2m\,\sinh^{-1}\frac{1}{2}\sqrt{Z_1Y_2},$$

in which θ'_1 and θ'_2 are the real and imaginary parts respectively of θ'.

If Z_1 be inductive, having components r and $j\omega L$, and Y_2 condensive, having components g and $j\omega C$,

$$\theta' = 2m\,\sinh^{-1}\frac{1}{2}\sqrt{(r+j\omega L)(g+j\omega C)} \quad (15)$$

$$= 2m\,\sinh^{-1}\frac{1}{2}\omega\sqrt{LC}\sqrt{\left(\frac{r}{\omega L}+jl\right)\left(\frac{g}{\omega C}+jl\right)} \quad (16)$$

and

$$T = \text{sech}\,2m\,\sinh^{-1}\frac{1}{2}\omega\sqrt{LC}\sqrt{\left(\frac{r}{\omega L}+jl\right)\left(\frac{g}{\omega C}+jl\right)} \quad (17)$$

By comparing Equation (17) with Equation (8) we see that these two equations are identical if it be assumed that

$$\sinh^{-1}\frac{\theta}{2} = \frac{\theta}{2} \quad (18)$$

The approximation in Equation (18) holds when θ does not exceed .5 to 1.0 radians from which it follows that the number of sections should be chosen so that the highest of the desired resonance frequencies corresponds to an angle of less than one radian per section. Formula (12), therefore holds true within certain limits for inductive-condensive lumped lines such as shown in Figs. 3 and 4 wherein Z_1 and Z_2 are in the form of inductance and capacity, respectively, and the correction factor of Equation (2) may be employed where the disparity is appreciable to determine the actual frequencies of resonance.

The foregoing mathematical analysis shows that voltages of certain frequencies may be greatly amplified by means of uniform or sectional lines.

With uniform lines the maximum amplifications will occur at frequencies harmonically related.

Lines of lumped constants may be designed so that the frequencies of maximum amplification are in approximately harmonic relationship through a considerable range.

The frequencies may depart from harmonic relationship if the design is appropriate for such departure. Although the principal emphasis in this specification is laid upon amplification of voltages of harmonically or nearly harmonically related frequencies it is contemplated that the principles herein set forth may be applied in designing modified arrangements to select and amplify voltages of frequencies in a great variety of relations.

In Fig. 5 is shown a typical line 20 adapted, in accordance with the present invention, to select and amplify certain odd harmonic voltages. The line comprises lumped series inductances L_1 and lumped shunt capacities C_2. Under Fig. 5 are given the formulæ applicable to the line 20. In Figs. 5[a] and 5[b] are graphs of the quantities θ', Z_1, and Y_2, and a graph indicating the resonance frequencies which comprise a fundamental and an indefinitely extended series of odd multiples thereof.

In Fig. 6 is shown another typical line 21 in which the lumped series inductance of adjacent sections have a mutual series aiding inductance M. The formulæ applicable to this line are shown in Fig. 6 and in Figs. 6[a] and 6[b] are graphs of the quantities θ', Z_1, and Y_2, and a graph indicating the selected frequencies. In connection with the graph of selected frequencies it is noted that the ratio $\frac{L_1}{M}$ controls the asymptotic limit of θ'.

In theory any number of resonance frequencies from one to infinity may be had by varying the ratio $\frac{L_1}{M}$.

By reference to Figs. 7 and 8 the solution of a practical problem may be illustrated. Let it be required to produce frequencies of 1,000 cycles, 3,000 cycles, 5,000 cycles etc., for application to a carrier suppression modulator. Let it be assumed that the source denoted by E in Fig. 7 is adapted to generate a voltage wave containing components of the desired frequencies and of such reactance as to properly form the end section of a line 20 similar to the line 20 of Fig. 5. A thermionic repeater 22 of very high input impedance terminates the line. The output circuit of the repeater 22 is coupled to a modulator 23 of the carrier suppression type which is supplied with oscillations of a frequency of 31,000 cycles per second from a source 24 for translating the selected wave frequencies to new values.

Let the surge impedance of the line 20 be 1,000 ohms and let it have ten sections. Neglecting resistance the iterative impedance

$$Z_0=\sqrt{\frac{L_1}{C_2}}=1{,}000 \text{ ohms.}$$

Since

$$\theta=\theta_1+jn\frac{\Pi}{2}$$

$$m\omega\sqrt{L_1C_2}=n\frac{\Pi}{2} \quad (20)$$

For the fundamental frequency

$$m\omega_0\sqrt{L_1C_2}=\frac{\Pi}{2}=m\cdot 2\Pi f_0\sqrt{L_1C_2}$$

Therefore,

$$\sqrt{L_1C_2}=\frac{1}{4f_0m}=\frac{1}{40{,}000}=.025\times 10^{-3}. \quad (21)$$

Whence $L_1=.025$ henries.

$C_2=.025$ microfarads

Now assume

$$Q_L=50 \text{ and } Q_c=\text{infinity},$$

whence

$$\theta=2m\sinh^{-1}\frac{1}{2}\omega_0\sqrt{L_1C_2}\underline{/89.°43}$$

$$=20\sinh^{-1}\frac{\Pi}{4}\underline{/89.°43}=\frac{\Pi}{2}\underline{/89.°43}.$$

$$T=\operatorname{sech}\theta=\operatorname{sech}\frac{\Pi}{2}\underline{/89.°43}=\operatorname{csch}\frac{\Pi}{200}=\frac{200}{\Pi}=64.$$

The value of T for 3,000 cycles, etc., may be similarly obtained in accordance with the comments following equation (12). If r and g are constant $T_n=T$ and the output current of the modulator 23 will have an amplitude varying with frequency as indicated in Fig. 8. The voltages of 26, 28, 30, 32, 34 and 36 kilocycles appear in the output circuit in greatly amplified form and may be selected by any suitable or known system of tuned circuits or other electrical networks and used, for example, to set up carrier waves in a carrier telegraph system. It is apparent that carrier waves may thus be produced for supplying waves constituting (1) a full harmonic system, (2) an odd harmonic system, (3) a non-harmonic equally spaced system or (4) a non-harmonic but unequally spaced system.

In Fig. 7[a] is shown a modified form of vacuum relay input circuit in which a high resistance 24 is connected across the grid-filament circuit in series with a source 25 for negatively polarizing the grid of the relay. The resistance 24 may have a value of the order of 1,000,000 ohms or more which makes the input impedance a sufficiently close approximation to the theoretically desirable infinite impedance.

Another use of the present invention is

in systems of radio or other frequency amplification where large amplifications are difficult to attain. By making use of the present invention for greatly increasing the voltage at a selected frequency or frequencies and applying the voltage thus increased to an electron discharge amplifier a large stable amplification can be attained. One or more stages of a multistage repeater may thus be replaced by a circuit in accordance with the present invention with advantages in selectivity and amplification.

The invention may be used in any case where frequencies which a line can be designed to amplify are to be selected and other frequencies attenuated or extinguished. The translating element or relay constitutes the high terminal impedance.

It is to be noted that the lines employed in carrying out this invention resemble certain types of filters described for example, in Campbell Patent No. 1,227,113, May 22, 1917. The selective phenomena, however, with which the present invention deals are present both in the transmitting and in the non-transmitting ranges of such filters as ordinarily used but principally in the transmitting range. Furthermore the terminations which such filters require and which are employed in practice would destroy the resonance phenomena upon which this invention depends.

The principles and mode of application of the invention having been described, the features believed to be novel are set forth in the appended claims.

What is claimed is:

1. A system for selectively amplifying a plurality of voltage waves comprising in combination, a wave source adapted to generate a plurality of waves of different frequencies, a space discharge amplifier including a control electrode, and an artificial line of recurrent structure composed of substantially non-dissipative reactances connected between said source and the control electrode and cathode of said amplifier, the reactances of said line being proportioned to produce resonances at the frequencies of the waves generated by said source, and the impedance of said source being negligibly small in comparison with the surge impedance of said line, whereby the effect of the line resonances is strongly intensified.

2. A system for the selective transmission of waves of harmonically spaced frequencies comprising in combination, a wave source adapted to produce a plurality of waves of harmonically related frequencies, a space discharge amplifier including a control electrode, and an artificial line of recurrent structure composed of substantially non-dissipative reactances connected at one end to said source and at the other end to the control electrode of the cathode of said amplifier, each section of said line comprising an inductance in series with the line and a capacity in shunt to the line, and the impedance of said wave source being negligibly small in comparison with the surge impedance of said line, whereby the effect of the line resonances is strongly intensified.

3. A line of recurrent sections of reactive elements having a source of voltage of a plurality of frequencies connected to one end and the input terminals of a space discharge relay connected to the other end, the impedance of said relay between its input terminals being more than one hundred times the surge impedance of the line, and the impedance of said voltage source being less than one hundredth part of the surge impedance of the line.

4. A system for selectively amplifying voltages of harmonically spaced frequencies comprising a low impedance source of harmonically related waves, a space discharge amplifier, and an artificial line having a plurality of recurrent sections of reactive elements, said line being connected at one end to the control electrode and cathode of said amplifier and being connected at the other end to said source, and further being so terminated at said source as to incorporate the reactive portion of the impedance of the wave source as an element of the line whereby the line is substantially short-circuited by said source.

In witness whereof, I hereunto subscribe my name this 16th day of October A. D., 1923.

TIMOTHY E. SHEA.