

July 22, 1947.

K. S. JOHNSON

2,424,238

TRANSMISSION LINE WITH ACTIVE NETWORKS

Filed April 20, 1943

2 Sheets-Sheet 1

FIG. 1

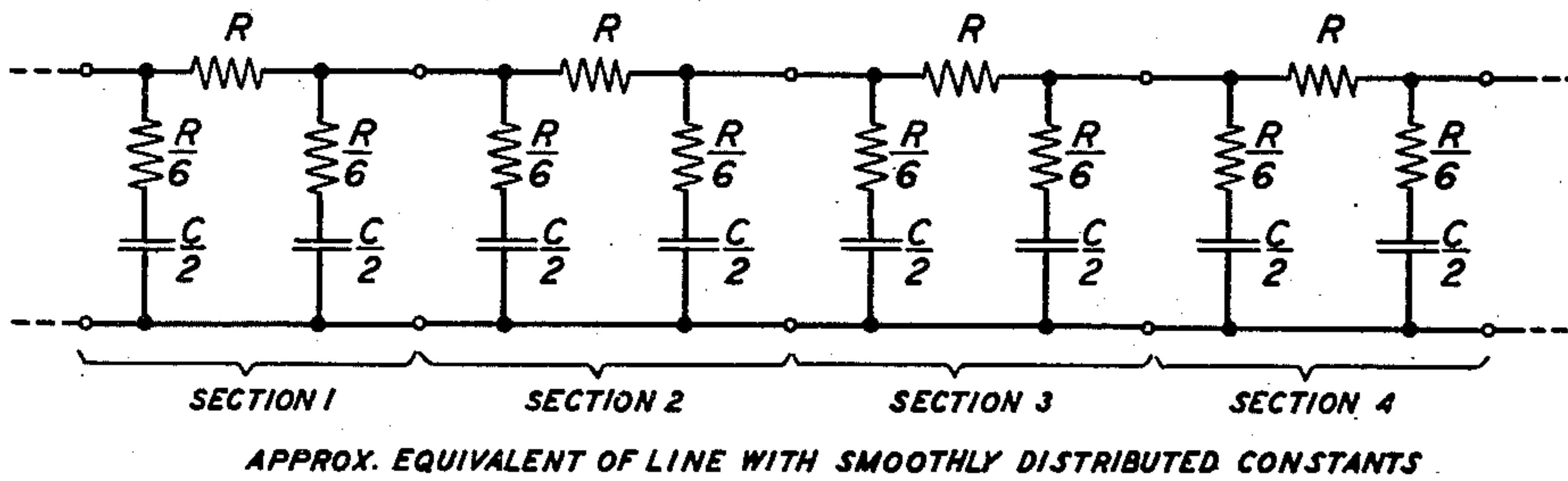


FIG. 2

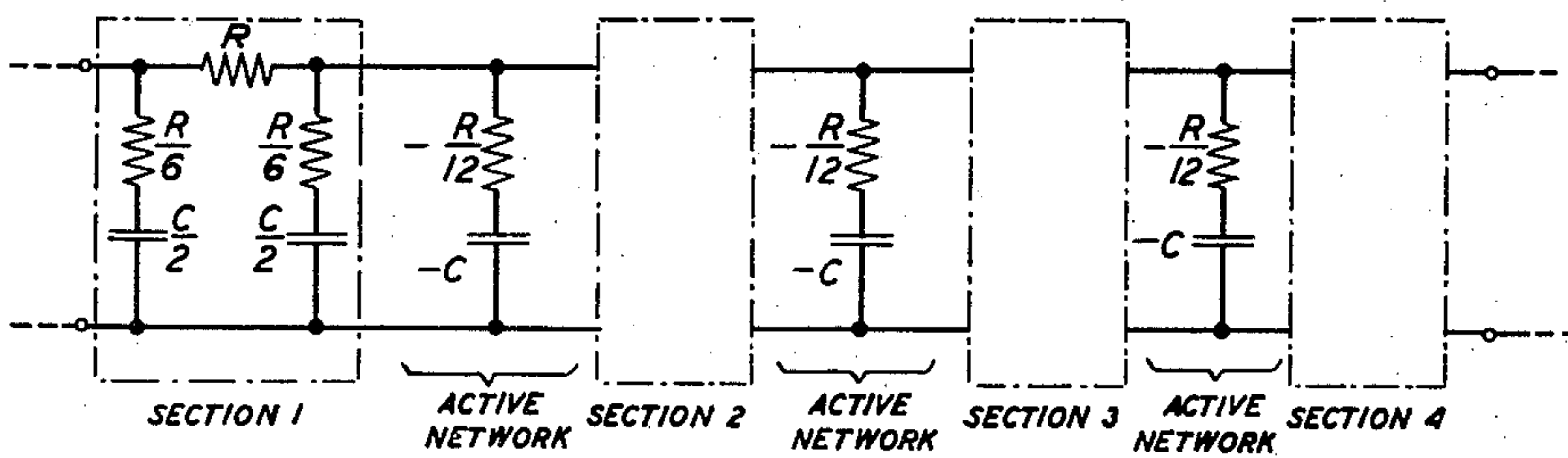


FIG. 3

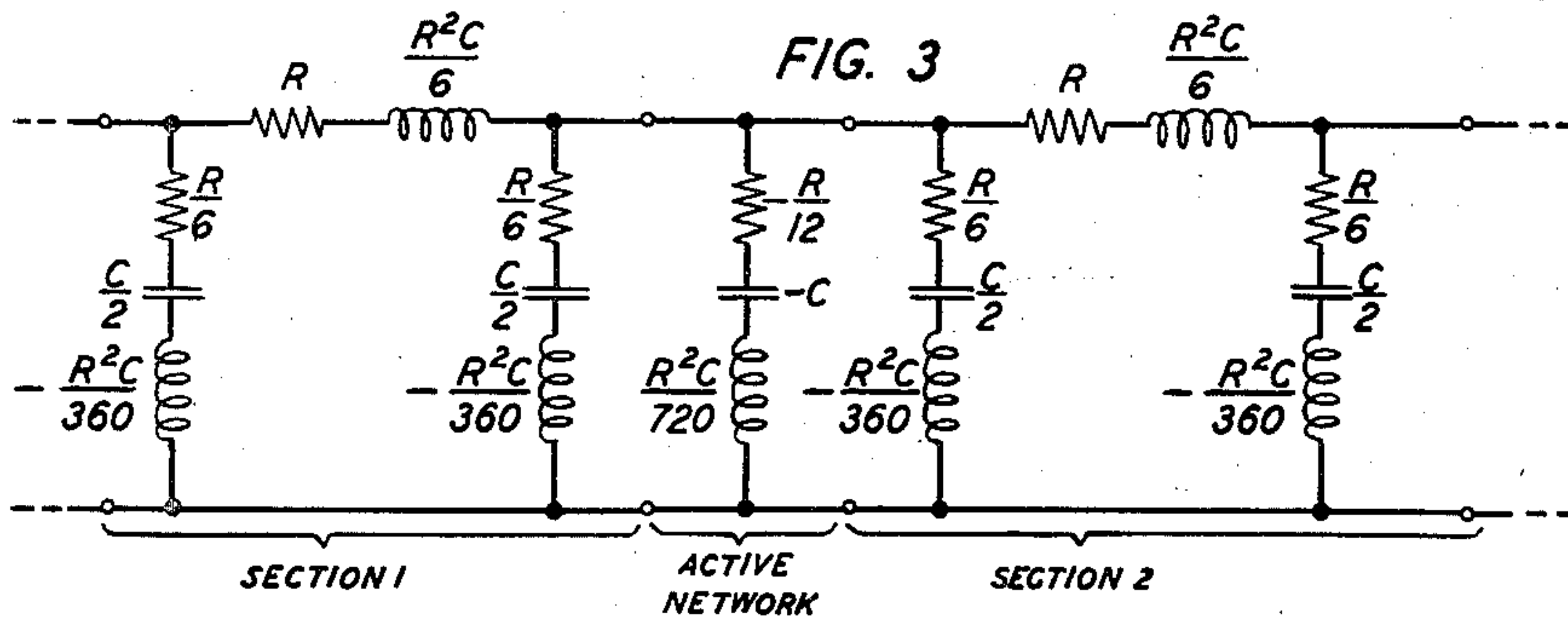
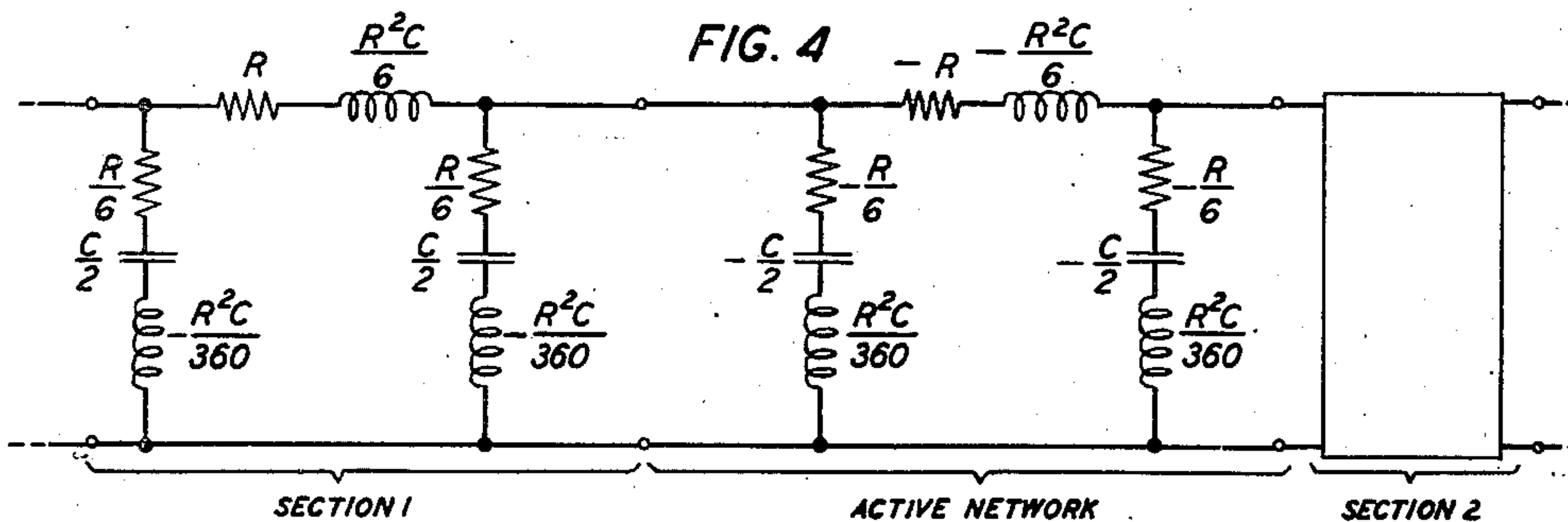


FIG. 4



INVENTOR
K. S. JOHNSON
BY *H. Abingers*
ATTORNEY

July 22, 1947.

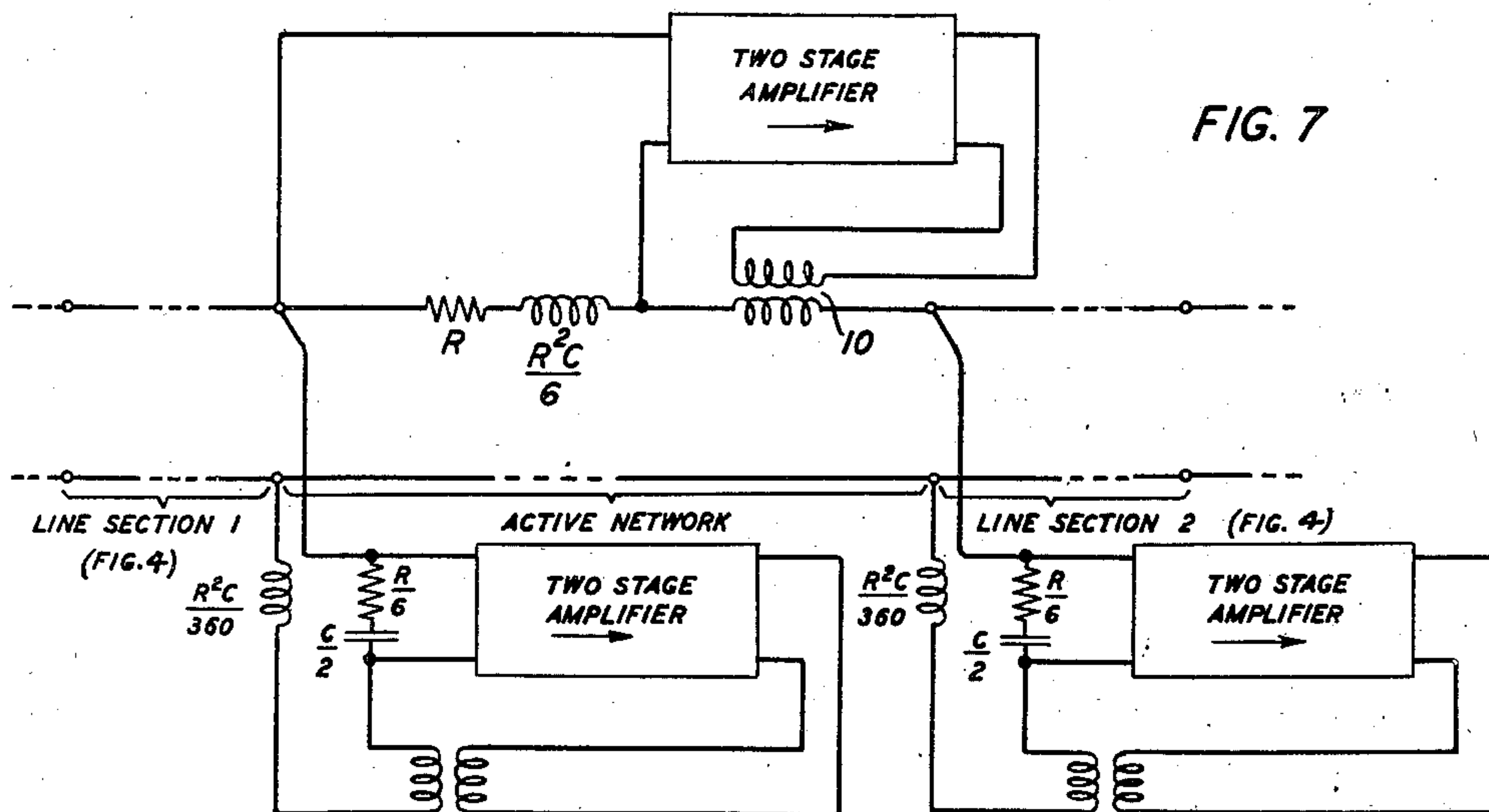
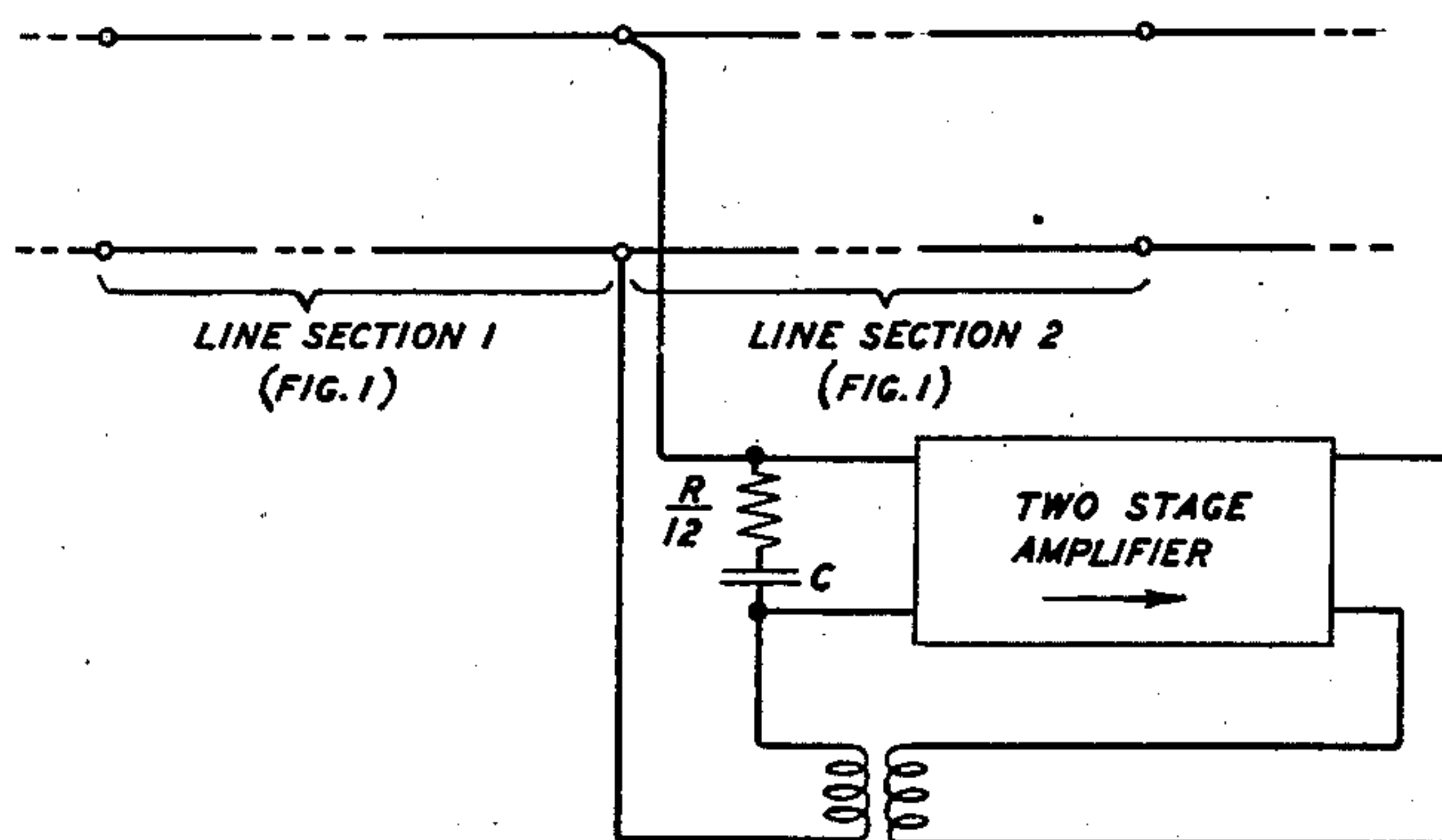
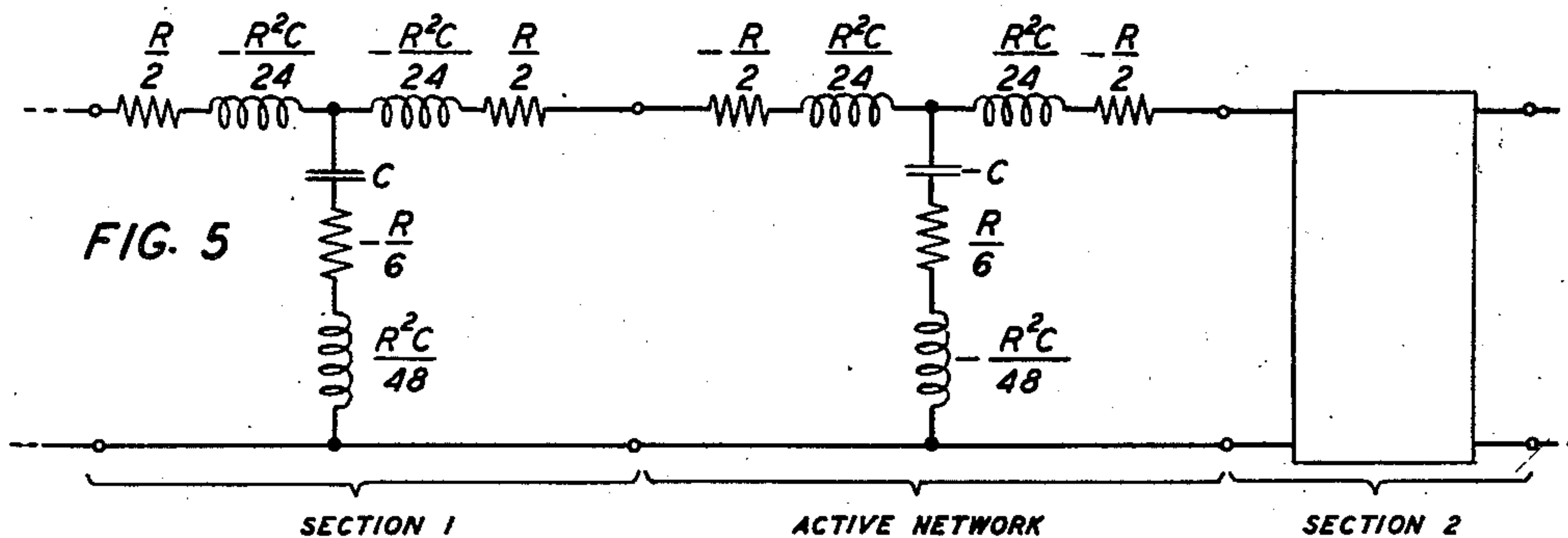
K. S. JOHNSON

2,424,238

TRANSMISSION LINE WITH ACTIVE NETWORKS

Filed April 20, 1943

2 Sheets-Sheet 2



INVENTOR
K. S. JOHNSON
BY *H. A. Burger*
ATTORNEY

UNITED STATES PATENT OFFICE

2,424,238

TRANSMISSION LINE WITH ACTIVE NETWORKS

Kenneth S. Johnson, South Orange, N. J., assignor to Bell Telephone Laboratories, Incorporated, New York, N. Y., a corporation of New York

Application April 20, 1943, Serial No. 483,753

8 Claims. (Cl. 178—44)

1

The present invention relates to the use of networks containing negative impedance for improving the transmission characteristics of a telephone line or other type of line.

In accordance with the invention, networks of lumped impedances are inserted at intervals in a transmission line, these networks each presenting an impedance which is the negative of the impedance of a section of the line.

In attempting to provide a network that will annul the transmission loss of a section of line the problem arises of finding a physically realizable localized network of lumped impedances which will sufficiently accurately represent the characteristic of the line for all the frequencies of interest.

Taking as a representative case a telephone cable pair, I have devised networks which are closely equivalent in transmission characteristic to a section of line several miles long. These networks are physically realizable, and by the aid of vacuum tube amplifier circuits the negative of the impedance of such a network can be effectively presented to the line in such a way as to largely annul or reduce the over-all attenuation.

The invention will be more fully understood from the following detailed description, taken with the attached drawing in which:

Fig. 1 is an impedance diagram of an equivalent smooth line;

Fig. 2 shows the line of Fig. 1 equipped with negative impedance networks or "active" networks, according to the invention;

Fig. 3 is a further representation, in terms of lumped impedances, of a smooth line equipped with two-terminal active networks according to the invention;

Fig. 4 shows a similar line equipped with four-terminal active networks according to the invention;

Fig. 5 shows a different manner of representing the equivalent impedance of a line and of applying a negative impedance network according to the invention; and

Figs. 6 and 7 show how the negative of given positive impedances may be obtained and effectively applied to a line.

I have found that a non-loaded cable pair with smoothly distributed resistance and capacitance (neglecting inductance and leakage) can be very closely represented by pi sections made up as in Fig. 1 where each section represents a length of line whose resistance is R and capacitance is C .

If now, as indicated in Fig. 2, there be inserted between each two adjacent sections a shunt net-

2

work made up of negative resistance of magnitude $R/12$ in series with negative capacitance of magnitude C , the resultant line has theoretically infinite shunt impedance and only the series resistance comprised of that of the sections in tandem. Such a structure will have theoretically no attenuation and maximum velocity of propagation. Actually, of course, zero attenuation could not be attained in any physical case. If attempt were made to connect negative resistance or negative impedance to its exact numerical positive equivalent, instability would result in practice. The rules for stability are well known and are given, for example, in Nyquist Patent 2,099,769, November 23, 1937. The rules for securing stability must be observed in setting up any practical embodiment of this invention but within the limitations imposed by stability requirements the invention permits one to approach as closely as desired to the condition of making the negative impedance of an active network equal to the positive impedance which it faces and so, in the case of a transmission line, reducing the attenuation and delay both to negligibly low values.

The type of line equivalent given in Fig. 1 has been referred to as a second order pi network this being a type having but two elements in its shunt arm. A considerably closer equivalent is represented in the third order network shown in Fig. 3, section 1, in which inductance is introduced into the equivalent network representing the line. Taking as a representative example a 19-gauge cable pair, calculations show that this type of section gives a nearly precise equivalent for 5-mile lengths of cable for all frequencies up to 4 kilocycles, and gives very close equivalence up to 10-mile lengths and up to 4-kilocycle frequency. Consequently, by bridging a two-terminal active network across the circuit every 10 miles or so, having the negative impedance elements shown in Fig. 3, the total shunt impedance becomes nearly infinitely great, the attenuation of the complete circuit approaches zero and the velocity of propagation has maximum value. This is due to the fact, of course, that the impedance of the active network as employed is essentially the negative of the total shunt impedance of the line itself so that the two impedances in parallel give a nearly infinite resultant.

The type of active network shown in Fig. 3 is capable of giving nearly infinite shunt impedance but the series impedance still remains uncanceled. By employing four-terminal active networks of the type and in the manner shown in Fig. 4, not

3

only is the shunt impedance made infinitely great but the series impedance is also made infinitely small thereby in effect theoretically wiping out all of the smoothly distributed circuit constants. In Fig. 4 the series branch of the active network is the negative of the series impedance of a section of line while each shunt arm of the active network is the negative of the shunt impedance of the line section which it faces.

In Fig. 5 the line is represented as composed of T-sections and the active networks are also T-sections in which the impedances are the negatives of analogous impedances in the equivalent line sections. This type of network, also, is capable of giving nearly zero series impedance and nearly infinite shunt impedance. The approximation is not quite as close with the T-section as with the pi section shown in Figs. 3 and 4 but the approximation is very close in the case of the T-section up to 5 miles of 19-gauge cable and for frequencies up to 4 kilocycles.

The manner in which the negative impedances assumed in the previous figures can be obtained is illustrated by two examples in Figs. 6 and 7. Fig. 6 is applicable to the case shown in Fig. 2, where a shunt comprising an element of impedance $-R/12$ in series with an element of impedance $-C$ is required. This is obtained by constructing a passive network of elements $R/12$ and C in series with each other and placing them in the input of an amplifier and also in shunt across the line in series with a feedback coupling from the output side of the amplifier. This is in accordance with the teaching of Patents 1,779,382 and 2,236,690 of R. C. Mathes which should be consulted for further disclosure of the exact circuit and method of operation. The phase relation around the amplifier and feedback paths must be proper and the degree of feedback adjusted to secure the desired effects.

Fig. 7 shows how the required negative impedances for Fig. 4 can be obtained. The shunt branches of the active network are similar to that of Fig. 6 except that the negative impedance derived from the amplifier is applied across the line in series with a positive inductance of value

$$\frac{R^2 C}{360}$$

It will be noted that this inductance is not included across the input terminals of the amplifier. The series arm is obtained by inserting R and

$$\frac{R^2 C}{6}$$

elements in series in the line and in the input side of a two-stage amplifier the output of which is back-coupled through a coil in series relation to the inserted positive elements.

The precautions against singing or instability discussed above in connection with Fig. 2 must, of course, be observed also in the case of the other embodiments. In these cases also the rules given by Nyquist are applicable. It is pointed out by Nyquist that a shunt type negative impedance is unstable when open-circuited or connected across a positive impedance of greater numerical magnitude than the negative impedance; and that a series type negative impedance is unstable when short-circuited or when connected in series with a positive impedance of smaller numerical magnitude than the negative impedance. It is, therefore, not practical to exactly equate the

4

negative impedance to the positive impedance in a circuit whether the negative impedance be of the series or shunt type since the circuit becomes practically unstable. The positive impedance must be at least slightly smaller in the shunt case and larger in the series case. The degree to which exact equality can be approached with impunity depends upon the particular conditions governing any case. Usually a margin of stability is left to take care of temporary or fortuitous changes in the system which might give rise to instability. The invention provides relationships which are nearly ideal as disclosed and in the use of the invention the ideal relationships may be as closely approached as given conditions in any case permit. For convenience of definition certain of the claims specify "substantially" certain values or state that the values are relaxed sufficiently to insure circuit stability. In view of the foregoing discussion of the question of stability, it is believed that these expressions are clear and definite.

The references to certain sizes of conductor and spacing of active networks and the other numerical values are to be taken as illustrative and not as limiting the scope of the invention, which latter is defined in the claims.

What is claimed is:

1. A transmission line of smoothly distributed constants having inserted therein at regular intervals a succession of active networks dividing the line into equal sections, each network including at least one branch shunted across the line and introducing across the line a negative impedance having as series components a negative resistance component and a negative capacitance component, said negative resistance component being numerically equal to a fraction of the series resistance of each section of said line between adjacent active networks, each line section being closely equivalent in transmission characteristics to a given symmetrical pi-network having its series arm substantially a lumped resistance and having in each of its two shunt arms a lumped resistance and a lumped capacitance in series, the product of said resistance and said capacitance in each of said shunt arms being numerically substantially equal to the product of said negative resistance component and said negative capacitance component, and the numerical ratio of said capacitance in each of said shunt arms to said capacitance in each of said branches being half the number of said branches per active network, said shunted networks rendering the line impedance substantially a resistance.

2. A wave transmission line with smoothly distributed resistance and capacitance having impedance bridged across said line at regular intervals, each bridging impedance having as series components a negative resistance component approaching a magnitude $R/12$ and a negative capacity component approaching a magnitude C , where the line impedance between bridging points is substantially equivalent to a pi network having for its series arm a resistance R and for each shunt arm a resistance $R/6$ in series with a capacity $C/2$, the degree of approach of the negative resistance and negative capacity values in the bridged impedances to the values stated being relaxed sufficiently to insure circuit stability.

3. A wave transmission line of smoothly distributed constants having impedances bridged across said line at regular intervals, each bridging impedance comprising two portions in series, the first portion having as series components a

5

negative resistance component approaching a magnitude $R/12$, and a negative capacity component approaching a magnitude C , and the other portion comprising a positive inductance approaching a magnitude

$$\frac{R^2 C}{720}$$

where the line impedance between bridging points is substantially equivalent to a pi network having for its series arm a resistance R in series with an inductance

$$\frac{R^2 C}{6}$$

and having for each of its shunt arms a resistance $R/6$, a capacity $C/2$ and a negative inductance of magnitude

$$\frac{-R^2 C}{360}$$

in series with one another, the degree of approach of said elements to the values stated being relaxed sufficiently to insure stability of the line against self-oscillation.

4. A wave transmission line of smoothly distributed constants having four-terminal active networks inserted therein at regular intervals, each such network being a pi network having for its series arm an impedance having two series components comprising a negative resistance component of magnitude substantially R and a negative component inductance of magnitude substantially

$$\frac{R^2 C}{6}$$

and for each of its shunt arms an impedance of two series portions, the first portion having as series components a negative resistance component of magnitude substantially $R/6$, and a negative capacity component of magnitude substantially $C/2$, and the other portion comprising an inductance of magnitude substantially

$$\frac{R^2 C}{360}$$

where the sections of line between the points of insertion of said active networks each has an impedance closely equivalent to that of a pi network having for its series arm a resistance R in series with an inductance

$$\frac{R^2 C}{6}$$

and for each of its shunt arms three elements in series comprising a resistance $R/6$, a capacity $C/2$ and a negative inductance of magnitude

$$\frac{R^2 C}{360}$$

each of the elements composing said active networks departing from the stated magnitude sufficiently to insure stability of the line against self-oscillation.

5. A wave transmission line of smoothly distributed constants having four-terminal active networks inserted therein at regular intervals, each such network being a T-network having for each of its two series arms two elements in series comprising a negative resistance of magnitude substantially $R/2$ and an inductance of magnitude substantially

$$\frac{R^2 C}{24}$$

and for its shunt arm a resistance of magnitude substantially $R/6$ in series with a negative impedance having as series components a negative

6

inductance component of magnitude substantially

$$\frac{R^2 C}{48}$$

5 and a negative capacity component of magnitude substantially C , where the sections of line between the points of insertion of said active networks each has an impedance closely equivalent to that of a T-network having for each of its two series arms a resistance $R/2$ in series with a negative inductance of magnitude

$$\frac{R^2 C}{24}$$

15 and for its shunt arm three elements in series comprising a capacity C , an inductance

$$\frac{R^2 C}{48}$$

20 and a negative resistance of magnitude $R/6$, each of the elements composing said active network departing from the stated magnitude sufficiently to insure stability of the line against self-oscillation.

25 6. A transmission line of smoothly distributed constants having networks inserted at regular intervals therein, each having a shunt arm comprising as series impedances an inductance of small numerical value compared with the series inductance of the line between adjacent networks, and a negative impedance whose series components are: a negative resistance component and a negative capacitance component, said negative resistance component being numerically a fraction of the value of the series resistance of the line between adjacent networks, said network substantially annulling the attenuation of said line.

40 7. A transmission line according to claim 6 in which said networks are four-terminal networks of pi-configuration, of which the series arm comprises a negative impedance having series components comprising a negative resistance component and a negative inductance component, and each shunt arm is a said shunt arm comprising an inductance in series with a negative impedance having as series components a negative capacity component and a negative resistance component.

45 8. A transmission line of smoothly distributed constants divided into equal sections each closely equivalent in its transmission characteristics to a symmetrical pi-network having a series arm substantially lumped resistance and two shunt arms, each comprising identical lumped impedance, and means for reducing the line attenuation and rendering the line impedance substantially a resistance, said means comprising a succession of active networks inserted in said line at regular intervals between said line sections, each of said active networks consisting of a shunt branch whose impedance is the negative of substantially one-half the impedance of a shunt arm of said equivalent pi-network.

KENNETH S. JOHNSON.

REFERENCES CITED

The following references are of record in the file of this patent:

UNITED STATES PATENTS

Number	Name	Date
2,137,696	Mouradian	Nov. 22, 1938
1,955,681	Mouradian	Apr. 17, 1934
1,687,253	Latour	Oct. 9, 1928

75