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H. NYQUIST

SYSTEM OF TRANSMISSION OVER LOADED LINES

Filed March 28, 1923

3 Sheets-Sheet 1

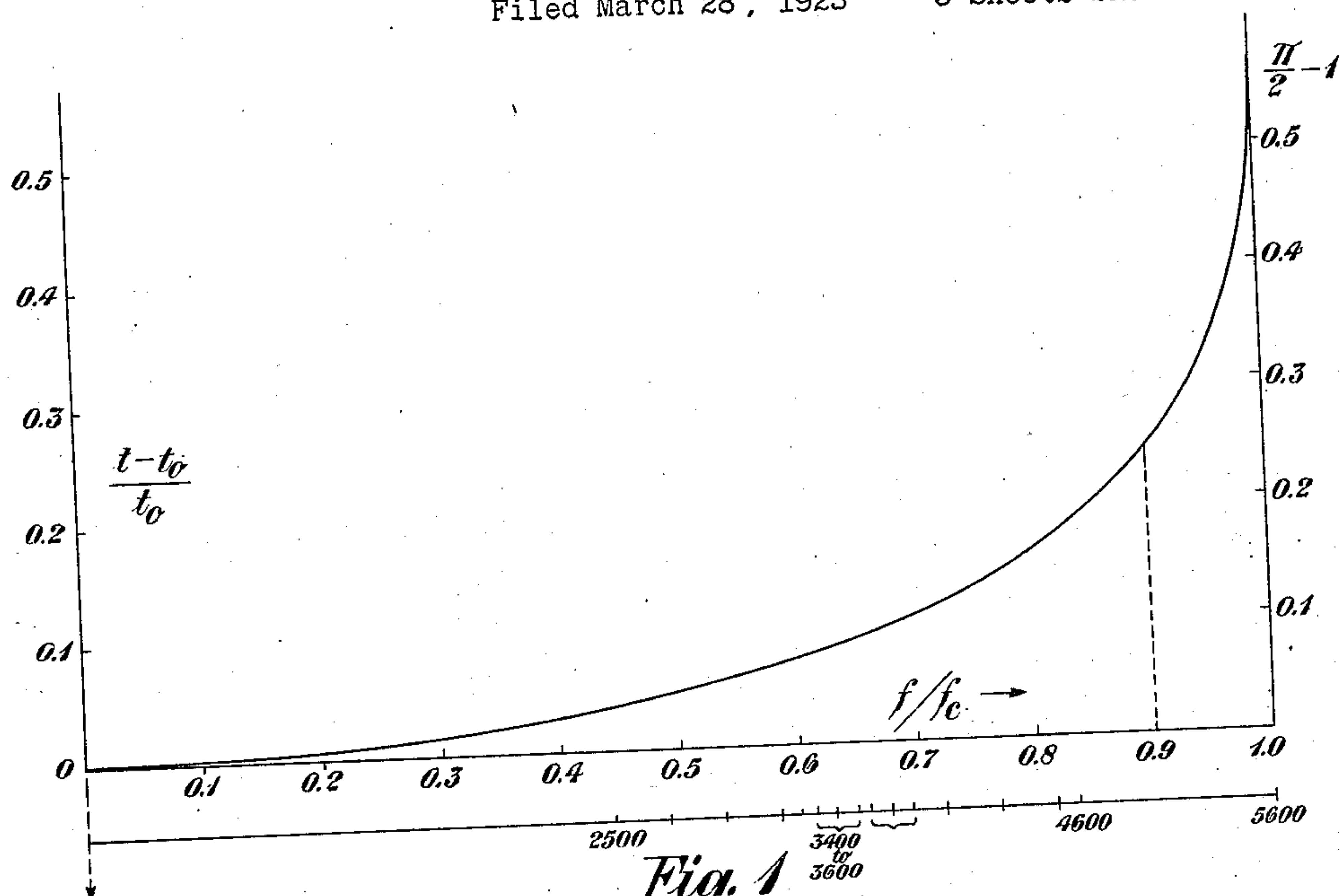


Fig. 1

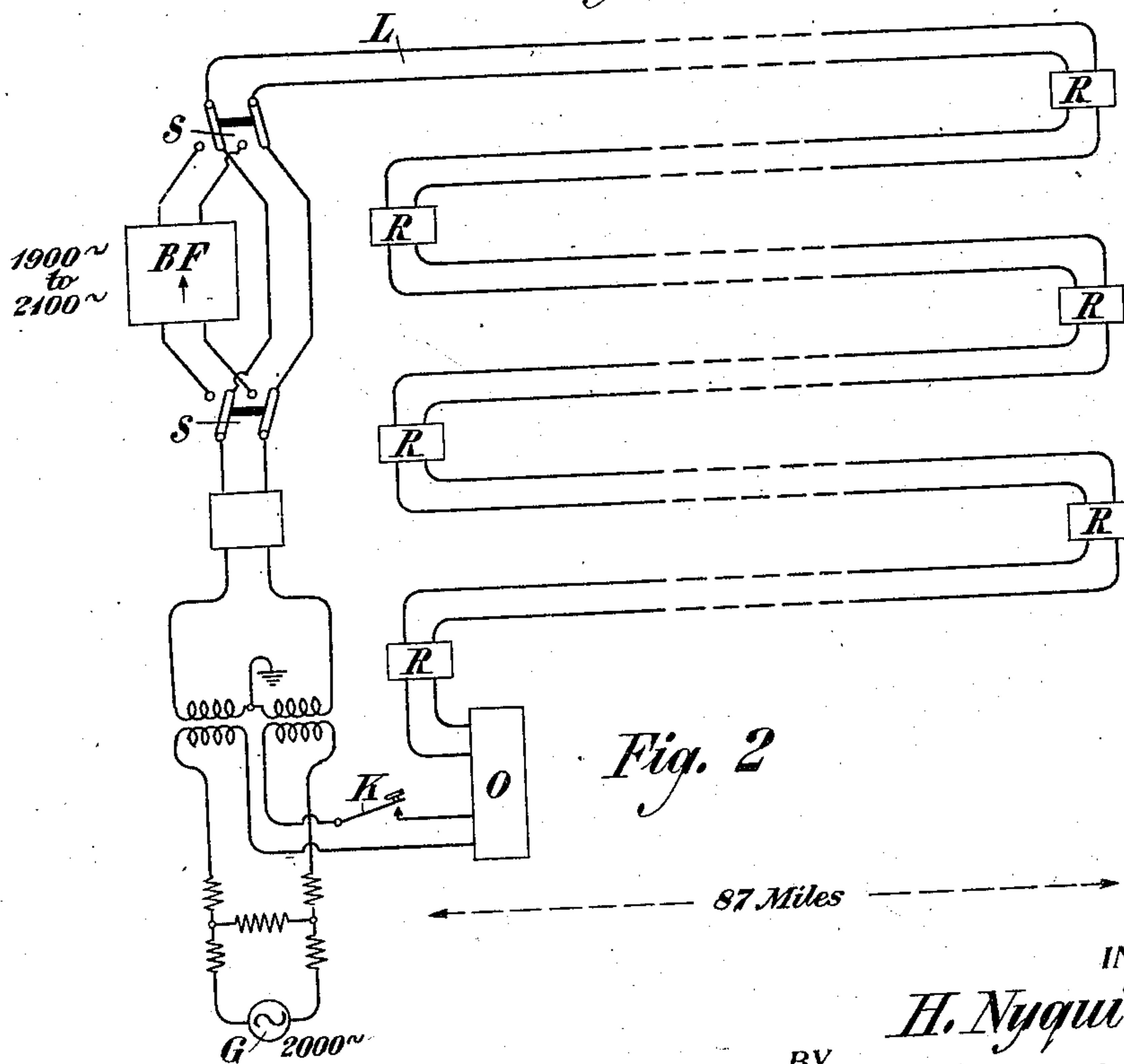


Fig. 2

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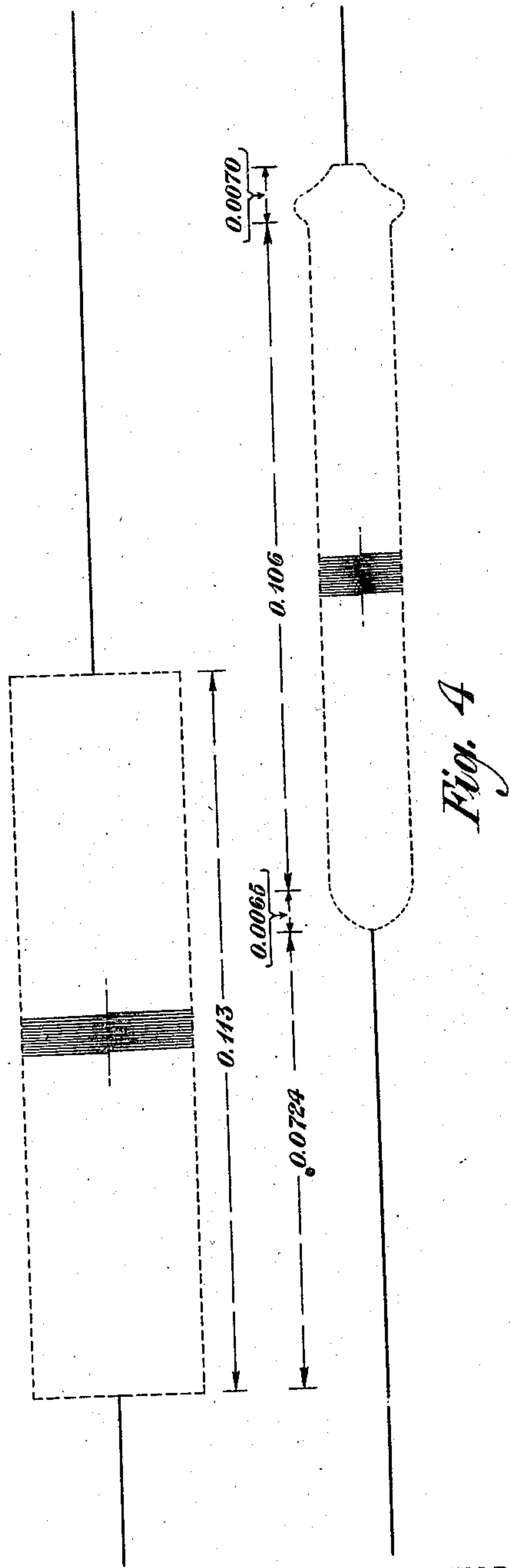
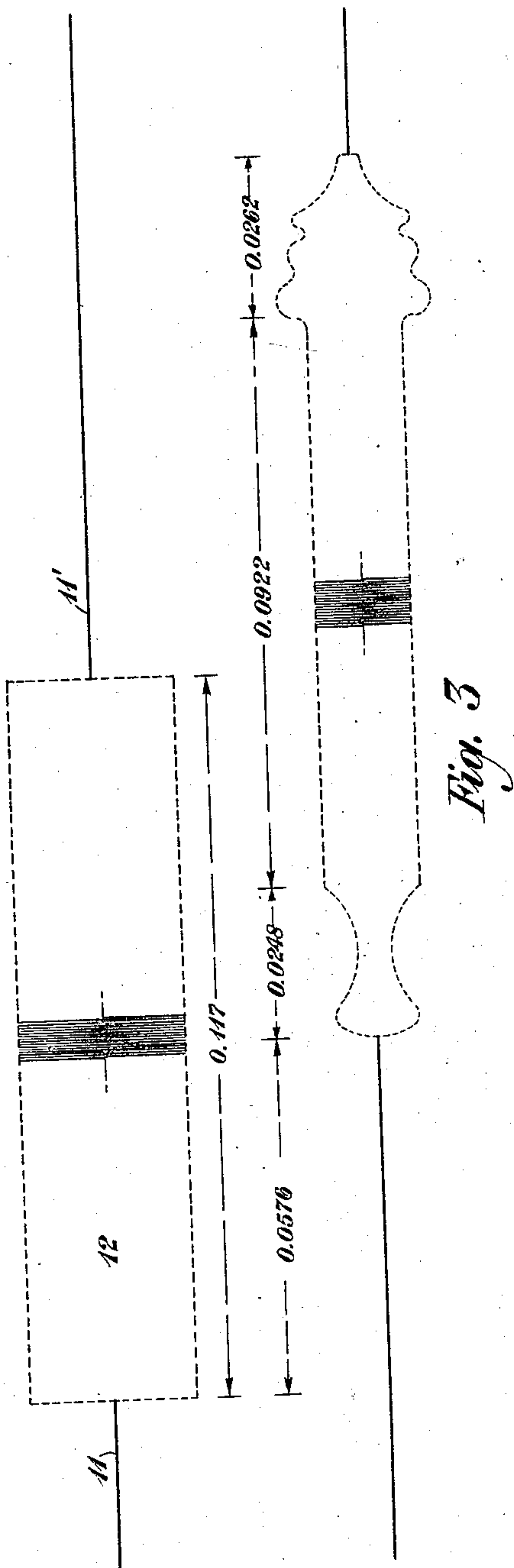
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3 Sheets-Sheet 2



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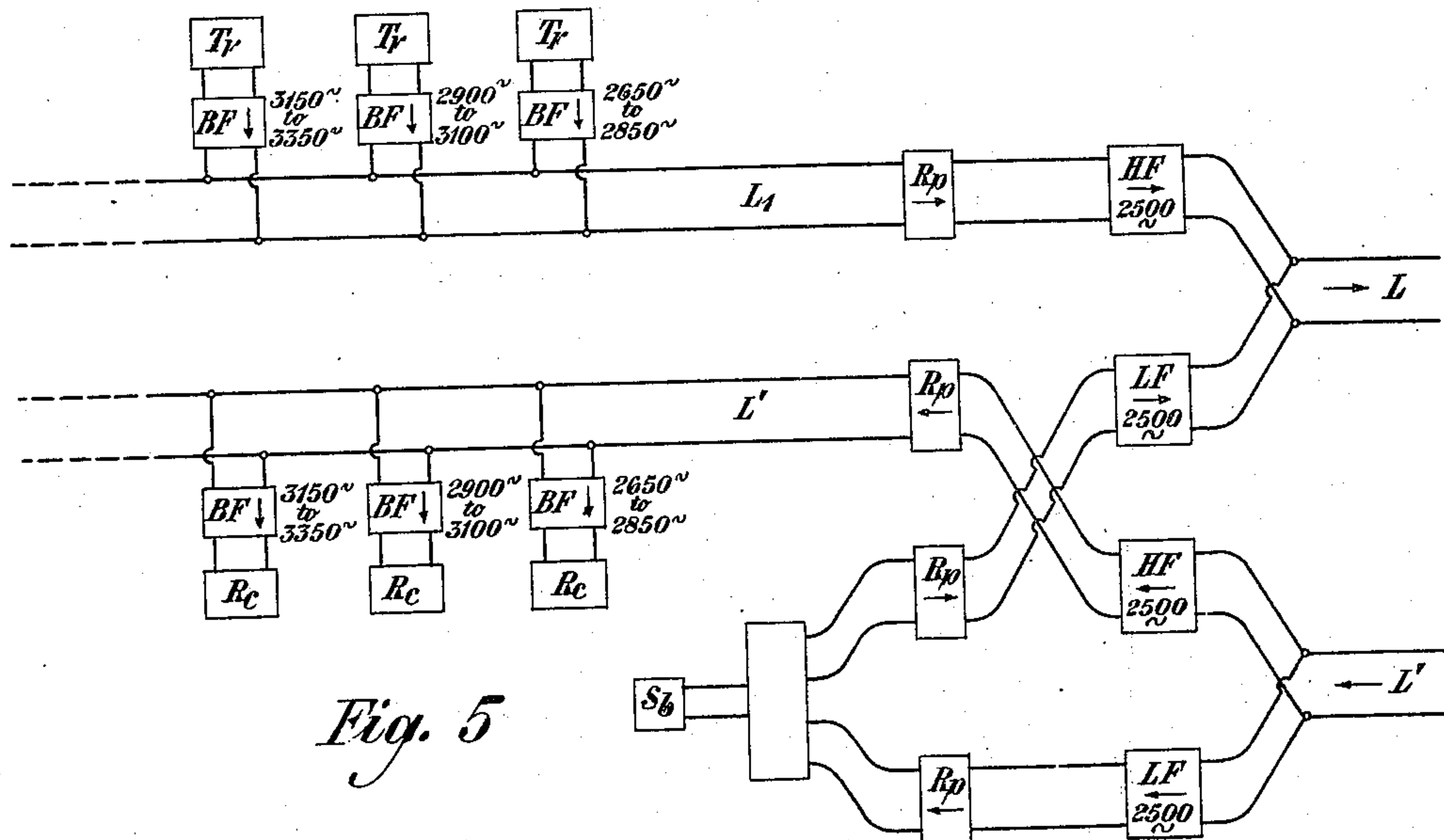


Fig. 5

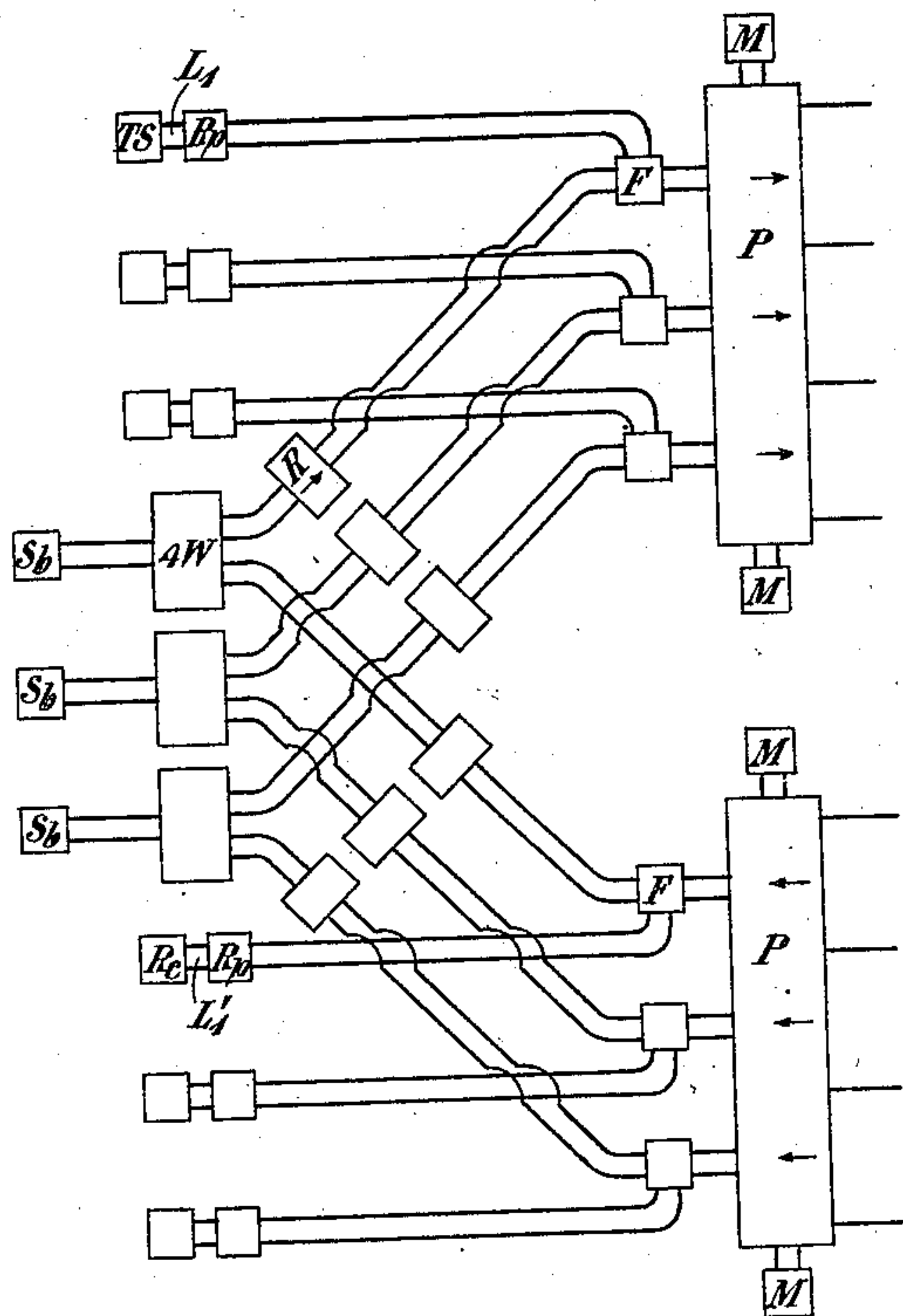


Fig. 6

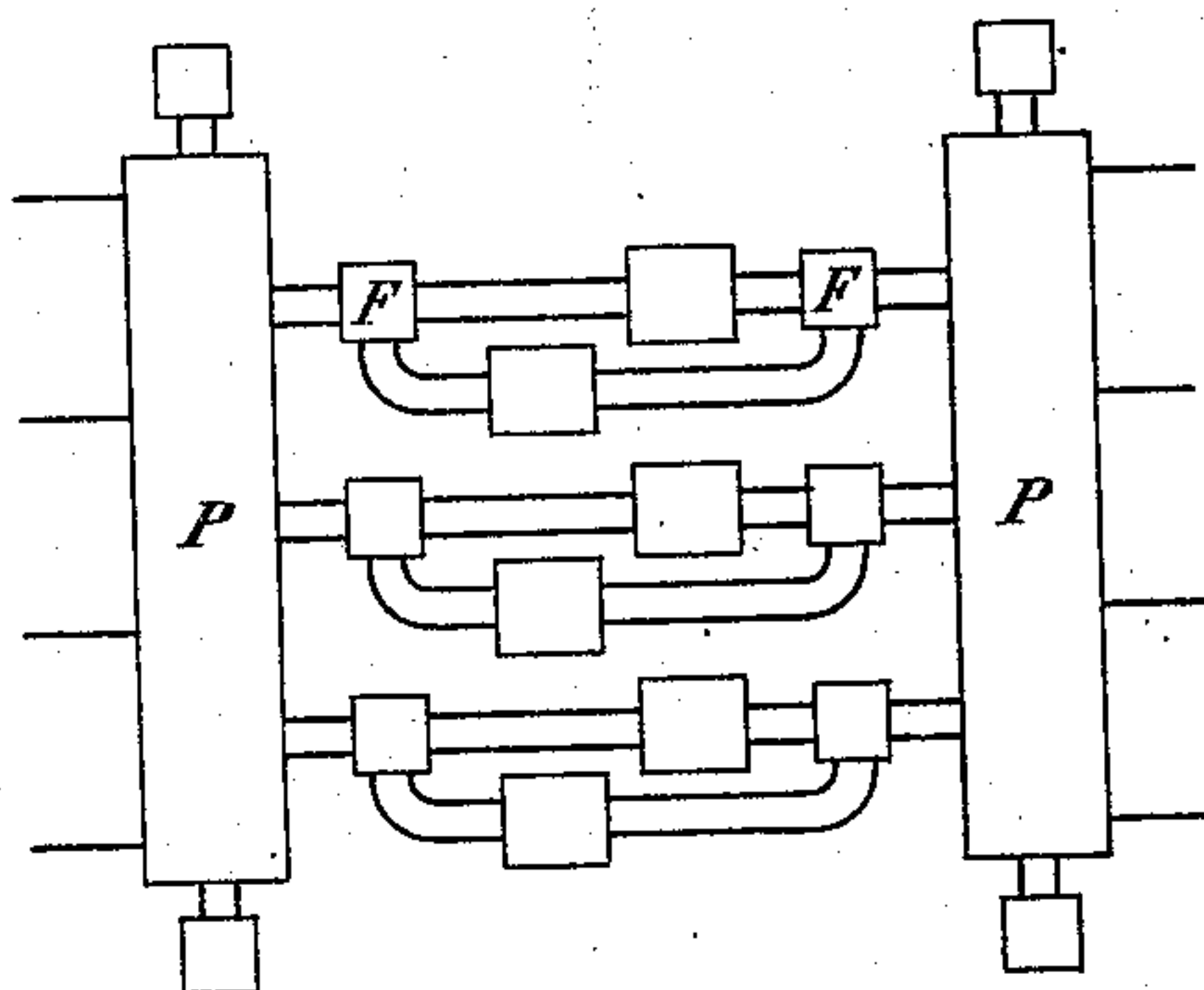


Fig. 7

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SYSTEM OF TRANSMISSION OVER LOADED LINES.

Application filed March 28, 1923. Serial No. 623,289.

An object of my invention is to provide for utilizing the available frequency range on a loaded line for transmission without harmful distortion. Another object is to improve the quality of voice transmission on a loaded line by separating off the higher frequency components below the critical frequency of the loaded line, and to utilize these higher frequency components for telegraph channels in a manner to effect transmission without harmful distortion. These and various other objects of my invention will become apparent on consideration of a limited number of examples of specific practice according to the invention which I have chosen to describe in the following specification.

It will be understood that the following description relates more particularly to these examples of my invention and that the scope of the invention will be pointed out in the appended claims.

Referring to the drawings, Fig. 1 is a curve diagram that will be referred to in explaining the character of the distortion on a loaded line. Fig. 2 is a diagram of simple apparatus to illustrate the principle involved in my invention. Figs. 3 and 4 show the character of oscillograms obtained in connection with the apparatus of Fig. 2. Fig. 5 shows apparatus for the practice of my invention in connection with a simple four-wire transmission line. Fig. 6 is a diagram of terminal apparatus for the practice of my invention in connection with phantom and side circuits operated on the four-wire principle; and Fig. 7 is a diagram of apparatus at a repeater station corresponding to the terminal apparatus shown in Fig. 6.

In transmission over a loaded line there is a certain critical frequency fixed rather definitely by the design of the line, such that the line transmits comparatively freely currents of any frequency below the critical frequency, but the line transmits higher frequencies only with extreme attenuation or practically it does not transmit them at all. As an example, a loaded line comprised in a cable may have its critical frequency at 5600 cycles per second. This means that frequencies below 5600 will be transmitted comparatively freely over the line while frequencies above 5600 applied to one end

of the line will produce no effect at the other end.

The frequency range essential for good voice transmission extends up to about 2500 cycles per second, but of course the voice quality will be improved somewhat if higher frequency components can be transmitted without distortion.

For voice transmission, distortion may be of two kinds—first, the components of various frequencies may be attenuated over the line in different degrees, and second, the components may be retarded differently. The first of these effects, viz, unequal attenuation, can be overcome by the use of an attenuation equalizer, and this expedient is well worked out in theory and practice. The second difficulty, unequal retardation of the components, may be somewhat serious in the case of a loaded line. If various frequencies are sent over a loaded line and if the time of arrival for the low frequencies is taken as zero, then the time for other frequencies, when plotted as ordinate against the frequency as abscissa, will give a curve such as that shown in Fig. 1. On the upper scale of abscissae, the ratio of the variable frequency to the critical frequency is laid off. The time of transmission for frequencies approaching 0 is taken as unity for the scale of ordinates. The equation of the curve shown in Fig. 1 is:

$$\frac{t-t_0}{t_0} = \frac{\sin^{-1} f/f_c}{f/f_c} - 1$$

It will be seen that over a frequency range from 0 to between 0.6 and 0.7 of the entire range up to the critical frequency, the retardation only attains about 10%, but for frequencies close to the critical frequency the retardation increases rapidly and may become as great as 50% or more. Hence, for voice transmission it may be that there will be a net improvement by cutting off these higher and much retarded frequency components.

The objectionable effect of the retarded frequency components may be exhibited in another way. In carrier current telegraphy the dots and dashes consist of trains of alternating current of a certain carrier frequency applied whenever the sending key is closed. But when a steady alternating E. M. F. is

applied to a line, the resulting current comprises various frequencies at the outset aside from the fundamental frequency, and these various other frequencies take an appreciable
 5 time to die away, so that there is a considerable interval of time after the steady alternating E. M. F. is applied until the steady state alternating current is reached. Then, supposing that the key has been closed
 10 to make a dash or a dot, when the key is opened to terminate the signal impulse, the current will die down in an irregular manner taking some time.

Three possible causes may be assigned for
 15 the length of the period of building up the current at the receiving end on the application of a steady E. M. F. at the sending end. In the first place the loaded line circuit has a definite cut-off frequency, the
 20 critical frequency, above which no current whatever is transmitted. Second, the transmitted components are unequally retarded in transmission depending on their frequency. Third, the attenuation for the transmitted
 25 frequencies differs from one value of frequency to another.

The first of these effects is known to be relatively unimportant for the reason that, if important, it would be present in a relatively
 30 short transmission line, whereas observation shows that the transient effects in a short loaded line are relatively insignificant. The third effect can be overcome by the use of attenuation equalizers, but after
 35 this is done there will be very considerable transient effects in long loaded lines, and they must be ascribed principally to the second of the three causes that have just been enumerated. This means that when a sinusoidal
 40 E. M. F. is suddenly impressed on a circuit, the resulting current may be regarded as made up of a large number of components varying in frequency from 0 to infinity. These components of different frequency
 45 travel along the transmission line at different rates of speed and recombine at the distant end to form the received current which is accordingly considerably distorted as compared with the transmitted current on account of the unequal retardation of the components. This unequal retardation is shown
 50 in Fig. 1.

Now suppose for an illustrative example that the carrier current frequency, that is
 55 the frequency of the sending E. M. F. is such that $f/f_c = 0.75$, and that a band filter is employed which cuts off all the frequencies below 0.7 and all above 0.8. From the curve in Fig. 1 it will be apparent that the greatest
 60 relative retardation within this frequency range is 0.05. With this small relative delay we should expect only a small distortion effect in the received signal.

From the foregoing it will be apparent
 65 that telegraph transmission should be im-

proved by the use of a band filter of narrow range including the carrier frequency at its mid-range. It should be remembered, however, that as the frequency range for the
 70 band filter is made narrower, the building-up time of the filter itself increases until a point is reached at which, with the very narrow range, the filter itself becomes the determining factor in the distortion of the
 75 received signal, and the differential retardation effect of the line will be substantially negligible.

A specific illustration of the principles that have been explained may be given by means of the apparatus shown in Fig. 2. At
 80 G is an alternating current generator with frequency 2,000. Upon the closure of the key K, an E. M. F. of this frequency will be applied to the line L. In this example the
 85 line L consists of three loops of loaded line each extending 87 miles and back, with six repeaters R as shown, and the output from the last repeater R goes to one element of the oscillograph O. Thus the length
 90 of the repeatered line is six times 87 miles or 522 miles. Another element of the oscillograph O is operatively connected to the sending circuit through the sending key K. By means of the switches S the band filter
 95 BF can be interposed when desired. Its frequency range is from 1900 to 2100.

When the key K is closed with the switches S in the position shown in Fig. 2, all the components in the range shown in Fig. 1
 100 are put upon the line and may get through to the receiving end in various degree. In this case the oscillogram has the character shown in Fig. 3. The film moves from right to left, and the oscillograph mirror which
 105 is associated with the sending key K gives the line 11 until the key K is closed, whereupon at 12 a sinusoidal curve appears, whose envelope is shown in dotted lines. On the opening of the key K the sinusoidal curve
 110 ends and the steady open-circuit condition is indicated by the line 11'. The period of closure of the key is seen to be 0.117 sec. The oscillogram for the received current is shown at the lower part of Fig. 3. The
 115 interval between the closure of the sending key K and the first received impulse is 0.0576 sec. Then comes a building-up period of 0.0248 sec. The envelope of the oscillogram is indicated in dotted lines, and it will
 120 be seen that at the end of the received signal impulse there is a transient effect lasting 0.0262 sec. Next the switches S are thrown in Fig. 2 so as to interpose the band filter which will cut off all the component
 125 frequencies below 1900 and above 2100. The effect is shown in Fig. 4, where with a sending impulse of 0.113 sec., the building-up period is reduced to 0.0065 sec. and the dying down transient disturbance period is only
 130 0.0070 sec. Thus the period of the initial

transient disturbance is reduced to about a fourth by interposing the band filter, and the period of the terminal transient disturbance is also only about one fourth as long as before. The interval after the key is closed until the first received impulse is felt is longer with the filter interposed, as would naturally be expected, 0.0724 sec. as compared with 0.0576 sec. With the improvement shown in Fig. 4 higher telegraph speed can be attained, because the initial and terminal ends of the received signal impulse will be less distorted.

The oscillograms of Figs. 3 and 4 were actually taken with a medium heavy loaded line that cut off at about 2800 cycles per second and the frequency employed was 2000 cycles per second, making $f/f_c = 0.71$.

In Fig. 5 I have shown how my invention may be practiced in connection with a loaded line operated according to the four-wire system by which two conductors of one circuit are employed for sending, and the two conductors of another circuit are employed for receiving. Transmitted voice currents originated by the subscriber at S₆ go, as shown by the arrows, through the repeater R_p and the low-pass filter LF to the line L. The critical frequency of the low-pass filter LF is 2500. Return voice currents coming from the distant subscriber over the line L' go through the low-pass filter and the repeater, as shown by the arrows, to the subscriber S₆.

Various sets of telegraph transmitting apparatus each designated T_r are connected through the respective band filters BF in multiple to the circuit L₁ which connects through the repeater R_p and the high-pass filter HF with the line L. The critical frequency for the high-pass filter HF is 2500. Each of the band filters BF transmits freely over the range indicated in the respective legends on the drawings. For example, one of them transmits between 2650 and 2850 cycles per second. This corresponds to a carrier frequency of 2750.

Received carrier current telegraph signal impulses coming in over the line L' are blocked by the low-pass filter LF but passed by the high-pass filter HF, as shown by the arrows, and then they go through the repeater to the branch circuit L₁'. The various telegraph receiving sets R_c are connected through respective band filters with this circuit L₁'. These band filters pass the frequency ranges indicated in the respective attached legends. It will be seen that if a telegraph operator at the distant station is sending on a carrier frequency of 3,000 cycles per second, his impulses will be blocked by all the band filters connected to the line L₁' except the middle filter of the three shown in Fig. 5 whose transmitting range is 2900 to 3100.

The telephone subscriber at S₆ in Fig. 5 and the party with whom he is talking at the other end of the line will have an improvement of the voice quality, because only those frequencies below 2500 will be involved in their conversation. The higher frequencies would be unequally retarded and would therefore produce distortion, but by the use of the high and low-pass filters, they will be kept out of the terminal apparatus involved in carrying on the telephone conversation.

Suppose the critical frequency for the loaded lines involved is 5600. A frequency scale from 0 to 5600 is laid off at the lower part of Fig. 1. Because of the steepness of the curve as it approaches 5600, it will not be practicable to use this part for telegraph channels, but the range from 4600 down to 2500 will be available. In this range eight telegraph channels may be provided with respective carrier current frequencies at 2750, 3000, 3250, 3500, 3750, 4000, 4250 and 4500. Each of these eight channels will be established by the use of a respective band filter with transmitting frequency range extending from 100 cycles below the carrier frequency to 100 cycles above. Thus, for example, one band filter will have its range from 3400 to 3600 corresponding to the carrier frequency 3500. The next filter will have its range from 3650 to 3850 corresponding to a carrier current frequency of 3750, and so on.

Telegraph transmission in each of these channels will be better than if the whole frequency range of the loaded line below 5600 were open as a single channel, because if that were the case, the components of frequency remote from the carrier would be unequally retarded and would give considerable distortion. The advantage of the band filters in improving the quality of the telegraph transmission is illustrated in connection with Figs. 3 and 4 as already explained.

In Figs. 6 and 7 I have shown the application of my invention in connection with a plurality of conductors in a cable where the pairs of conductors are operated as side circuits and in quads as phantom circuits. A terminal station is shown in Fig. 6. Composite phantom units are shown at P, the one above for sending and the one below for receiving. The usual superposed metallic telegraph apparatus is taken off from the phantom units as indicated by the apparatus designated M. Connected with each phantom unit P are three local circuits as shown. Three subscribers' sets are indicated each by the symbol S₆. Each is connected with a four-wire terminal apparatus 4W. Transmitted voice currents go through the repeaters R and filter sets F to the phantom unit P as indicated by the arrows. It will

at once be seen also how received currents coming in over the lower right-hand quad go to the subscribers' sets Sb. The telegraph transmitting sets are each indicated by the symbol TS, each such symbol indicating eight transmitting sets with their respective band filters. These are all connected by the line L_1 with the repeater Rp, L_1 being the same branch circuit as designated by that character in Fig. 5. From the repeater Rp a circuit connection is made to the filter set F and thence to the phantom unit P.

The symbol Rc designates eight sets of telegraph receiving apparatus each with its respective band filter, all connected in multiple by the conductor pair L_1' with the repeater Rp, from which connection goes to the filter set F and thence to the phantom unit P.

Each quad is repeated as shown in Fig. 7. Between the two phantom units P three conductor pairs are shown, one for each side circuit and one for the phantom circuit. Each pair of conductors leads from the phantom unit to a filter set which separates the low and high frequencies. These are amplified in the respective repeaters provided for that purpose and combined in the filter set F and returned to the phantom unit P.

By the use of my invention the quality of transmission for both telephone and telegraph messages can be improved in connection with loaded lines. This improvement is gained without sacrificing the available frequency range for carrier current transmission, but on the other hand this range is fully utilized.

I claim:

1. In combination, a loaded line, filters to separate component currents of various frequencies thereon into a practicable voice range and a higher range and band filters to establish a plurality of telegraph channels in said higher range below the critical frequency of the loaded line.

2. In combination, a line having the property of retarding currents of different frequencies in substantially unequal degree, and means to establish a plurality of channels, each of comparatively narrow frequency

range whereby the differential retardation within each such range will be substantially negligible.

3. The method of improving carrier current telegraph transmission on a loaded line, which consists in putting currents of various frequency components on the line and separating by at least one filter those components whose frequency is considerably different from the carrier frequency.

4. The method of utilizing a frequency range with substantially unequal retardation at various frequencies which consists in separating it into channels of different width with the narrower channels in the part of the range where the differential retardation is greater.

5. In combination, a loaded line having a certain critical frequency below which it transmits current components with different retardation according to their frequency and above which it transmits substantially no current, filters to separate current components of different frequencies on the line into a range below approximately 2,000 cycles per second and a range above that frequency and further to separate the last mentioned range into a plurality of telegraph channels.

6. In combination, a loaded line having the property of cutting off all currents of frequencies above a certain critical frequency and of substantially differently retarding the components below that frequency, and means to establish a plurality of channels each of comparatively narrow frequency range whereby the differential retardation within each such range will be substantially negligible.

7. The method of improving the quality of transmission by carrier current on a loaded line which consists in employing a comparatively narrow range of frequencies for the current components within a single channel and separating therefrom currents of other frequencies.

In testimony whereof, I have signed my name to this specification this 27th day of March, 1923.

HARRY NYQUIST.