A VARIABLE AMPLIFIER VALVE WITH DOUBLE CATHODE CONNECTION SUITABLE FOR METRE WAVES

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A great disadvantage of ordinary amplifier valves in the amplification of very high frequencies is the damping of the oscillator circuit connected with the control grid, due to the coupling between control grid circuit and anode circuit *via* the self-induction of the cathode connection. This disadvantage can be avoided by providing the cathode with two connections, which belong respectively to the control grid circuit and the anode circuit. By using these two connections of the cathode in a suitable manner numerous possibilities of connection occur so that it is possible to eliminate the damping of control grid circuit and anode circuit simultaneously, and at the same time to influence the reactance in a favourable manner. In this article a variable amplifier valve with a double cathode connection (EF 51) is described, which for wave lengths not shorter than 1.5 m gives approximately as satisfactory results as the (non-variable) push-pull amplifier valve EFF 50, and considerably better results than the existing button pentodes.

For the satisfactory performance of electronic valves which are intended for the amplification of very short waves it is essential that particularly the noise resistance, the input damping and the output damping should be low, while at the same time a steep slope must be retained. A steep slope, however, as explained previously in this periodical [1]), causes great damping of the input circuit due to the self-induction of the cathode connection. In the second article referred to, a valve was described in which this objection is met by the application of the push-pull principle. This valve, type EFF 50, can be used successfully for the amplification of signals with frequencies up to 6×10^8 c/s (wave length 50 cm), at which frequency an amplification by a factor 8 can still be obtained.

The principle upon which the push-pull amplifier valve is based consists in the fact that two systems which work in exactly opposite phase are connected to a common cathode connection. Since the sum of the high-frequency currents in the two systems is equal to zero, no high-frequency current flows through this cathode connection, and its self-induction can therefore have no damping effect on the input circuit.

The result obtained in this way answered fully to the expectations. In practice, however, it is not always possible to use a push-pull valve. It therefore became necessary to find out whether the aim in view — combatting the damping effect of the cathode connection — could not be attained by some other method as well.

A constructively simple principle, which offers many possibilities of influencing the input damping, the output damping and in addition the reactance in a favourable way, consists in the use of a **double cathode connection**. The anode current which returns to the cathode *via* one of the cathode connections then no longer needs choose a path which comprises part of the input circuit which is connected to the other cathode connection between grid and cathode (see *fig. 1b*).

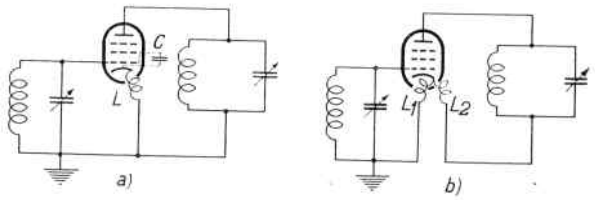

Fig. 1. Connections of a valve with single cathode connection (*a*) and of a valve with double cathode connection (*b*) in a stage for high-frequency amplification. Only the impedances important for high-frequency currents are given. In case *a* the self-induction L forms part of the input circuit and part of the output circuit at the same time, so that a back coupling occurs which is lacking in case *b*.

In order to show that by this means the damping effect of the anode current on the control grid circuit actually does disappear, we shall briefly review the theory of the input damping due to the self-induction of the cathode connection. If v is the A.C. voltage on the input circuit of fig. 1*a* and i_a the anode A.C., then the A.C. voltage between control grid and cathode is approximately:

$$v_g = v - j\omega L\, i_a$$

and therefore the A.C., which will flow to the control grid due to the presence of the grid-cathode capacity C, amounts to

$$i_g = j\omega C\, v_g = j\omega C v + \omega^2 LC\, i_a$$

In the first approximation $i_a = Sv$ where S is the slope of the valve, and therefore

[1]) M. J. O. Strutt and A. van der Ziel, The behaviour of amplifier valves at very high frequencies, Philips techn. Rev. **3**, 103, 1938; A new push-pull amplifier valve for decimetre waves, Philips techn. Rev. **5**, 172, 1940.

$$i_g = (j\omega C + \omega^2 LCS)\, v.$$

The second term in parentheses represents a current component which is in phase with the voltage, so that energy is taken from the input circuit. The equivalent input parallel resistance is

$$R_L = 1/\omega^2 LCS \quad . \; . \; . \; . \; . \; . \quad (1)$$

(The subscript L indicates that the self-induction of the cathode connection is the cause of the damping).

In the connections with two cathode connections given in fig. 1*b* the anode current has no effect on the voltage between control grid and cathode, so that the above-discussed damping effect is entirely absent.

We need not stop at this result, however, but by the addition of suitable circuit elements we may even obtain negative damping of the input circuit, as will be explained in the following. After having shown further that the output damping and the reactance can also be favourably affected by suitable use of two cathode connections, we shall describe the construction of a valve, namely the high-frequency amplifier valve EF 51 which, for waves no shorter than 1.5 m, possesses properties which are much more favourable than those of the existing button pentodes and only slightly less satisfactory than those of the push-pull amplifier valve EFF 50. Compared with the push-pull amplifier valve the new high-frequency valve has the advantage that it offers the possibility of varying the amplification by varying the slope of the valve.

The influence of two cathode connections on the input damping

For the sake of simplicity of expression in the following we shall define several of the terms to be used. By the first cathode connection we mean the cathode connection which belongs to the input circuit, while the second cathode connection belongs to the output circuit. The end of the cathode connection which extends outside the valve will be called the lower end; the upper end is thus connected to the cathode.

In order to profit by the double cathode connection for the purpose of decreasing the damping of the input circuit, another condenser C_1 must be added to the circuit elements given in fig. 1*b* between the lower end of the second cathode connection and the control grid. In this way the diagram of *fig. 2* is obtained. It is immediately clear that the A.C. voltage which occurs due to the self-induction of the second cathode connection, *via* the condenser C_1 will now lead to a grid A.C., as was the case in the ordinary connections according to fig. 1*a*. Since the condenser C_1 is connected to the lower end of L_2, however, this A.C. is opposite in phase to that which occurred in the case of fig. 1*a*, so that instead of a damping a negative damping is obtained.

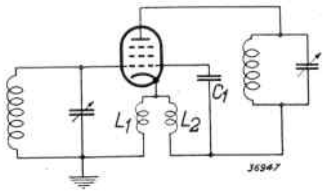

Fig. 2. Connection to two cathode connections and an auxiliary condenser C_1 for the purpose of eliminating the damping of the input circuit.

By analogy with equation (1) we obtain as value of the equivalent parallel resistance by approximation:

$$R_{L_2} = -1/\omega^2 L_2 C_1 S \quad . \; . \; . \; . \; . \quad (2)$$

This negative damping can be used for instance to decrease, or even entirely to eliminate the damping of the input circuit which occurs as a result of the finite transit time of the electrons between cathode and control grid [2]). This damping of the transit time, in the case of the valve EF 51 discussed later, corresponds approximately to a resistance

$$R_e = \frac{36}{f^2}\, 10^{-6}\ \Omega$$

where f is expressed in megacycles per second. If we attempt to compensate this damping with the help of the negative damping action of the second cathode connection, the sum of the damping by R_e and R_{L_2} must disappear as follows:

$$\omega^2 L_2 C_1 S = \frac{f^2}{36} \cdot 10^{-6} \quad . \; . \; . \; . \; . \quad (3)$$

The slope S of the valve EF 51 amounts to about 10 mA/V. Moreover $\omega = 2\pi f \times 10^6$, so that for the unknown circuit elements C_1 and L_2 we obtain the condition:

$$L_2 C_1 = \frac{10^{-15}}{10 \cdot 36 \cdot 4\pi^2} = 7 \cdot 10^{-20} \text{ farad henry.} \quad (4)$$

If we choose for C_1 a capacity of 1 picofarad then the self-induction of the cathode connection L_2 must be 7×10^{-8} henry, which is obtained by a wire about 6 cm long and 1 mm in diameter. We thus obtain elements which can easily be realized

[2]) See C. J. Bakker, Philips techn. Rev. 1, 171, 1936.

in practice. The damping elimination indicated is valid for the whole range of short waves, since the value of L_2C_1 determined by equation (4) is independent of the frequency.

The influence of two cathode connections on the output damping

If in addition to the input damping we also wish to influence the output damping in a favourable direction, a second auxiliary condenser C_2 must be placed between the anode and the lower end of the first cathode connection (see *fig. 3*). If e_a is the

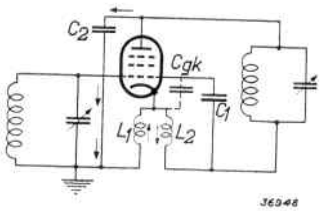

Fig. 3. Connection with two cathode connections and two auxiliary condensers C_1 and C_2 for the purpose of eliminating the input and the output damping. At the same time C_2 leads to a reactance capacity between anode and control grid, and thereby compensates the negative reactance capacity which is present at short waves due to other causes.

anode A.C. voltage over the oscillator circuit, then by approximation the following A.C. flows through this condenser:

$$i_{C_2} = e_a\, j\omega C_2, \quad .$$

along the path indicated by arrows *via* the self-inductions L_1 and L_2. Between cathode and earth therefore an A.C. voltage occurs:

$$v_k = -\,j\omega\, L_1\, i_{C_2} = e_a\, \omega^2\, L_1 C_2.$$

This change in the cathode potential leads to an extra anode current $-Sv_k$, thus $-e_a\,\omega^2 L_1 C_2 S$. From this it is evident that a negative damping also occurs in the anode circuit, which is determined by a formula quite analogous to the negative damping of the grid circuit.

In almost all connections occurring in practice the anode circuit of the high-frequency amplifier valve is coupled with the input circuit of a second stage, for instance a second amplifier valve or a mixing valve. The negative damping of the anode circuit is at the same time a negative damping of the input circuit of the following stage so that in the latter the damping need not be eliminated or only to a smaller extent.

The influence of the two cathode connections on the reactance of the cathode on the control grid

As was stated in the discussion of the output damping, the A.C. voltage e_a over the anode circuit leads to an A.C. along the path indicated by arrows (in fig. 3). This A.C. causes the A.C. voltage mentioned between cathode and earth:

$$v_k = e_a\, \omega^2\, L_1\, C_2$$

The A.C. flows further through the second cathode connection (self-induction L_2), so that the lower end of the latter possesses the following A.C. voltage with respect to earth:

$$v = e_a\, \omega^2\, (L_1 + L_2)\, C_2$$

These two A.C. voltages result in alternating currents to the control grid *via* the capacities C_{gk} and C_1, respectively. These capacities connect the control grid to points on which an A.C. voltage acts which is in phase with the anode A.C. voltage, but which has a much smaller amplitude. The effect of the A.C. voltages v_k and v on the control grid circuit is therefore exactly the same as if the capacities C_{gk} and C_1 were connected between control grid and anode, not with their whole magnitude, however, but reduced by a factor v_k/e_a and v/e_a. The total apparent capacity hereby caused between control grid and anode thus amounts to:

$$C_{ag}' = C_{gk}\frac{v_k}{e_a} + C_1\frac{v}{e_a} =$$
$$= \omega^2 C_2\,[L_1\,(C_{gk} + C_1) + L_2C_1] \quad . \quad . \quad (6)$$

This apparent capacity is now found to reduce the reactance at high frequencies, since the reactance already present due to other causes has at high frequencies the character of a negative apparent capacity [3]), which like that of equation(6) is proportional to the square of the frequency. The size of this apparent capacity C_{ag}'' depends upon the manner of connection, and at a wave length of 2 m, for example, may amount to 0.2 pF. This would correspond to a behaviour according to the formula

$$C_{ag}'' = -2.25\cdot 10^{-19}\,\omega^2\ \mathrm{pF} \quad . \quad . \quad . \quad . \quad (7)$$

If the total reactance must just be made to disappear, care must be taken that

$$C_2 = \frac{2.25\cdot 10^{-19}}{L_1\,(C_{gk} + C_1) + L_2C_1} \quad . \quad . \quad . \quad (8)$$

The capacity C_2 to be calculated from this, as was already indicated in the previous section, gives at the same time a negative damping of the anode circuit; in the case of the valve EF 51 this is found to be more than enough to combat the causes of damping present.

[3]) See the first article referred to in footnote [1]), p. 113.

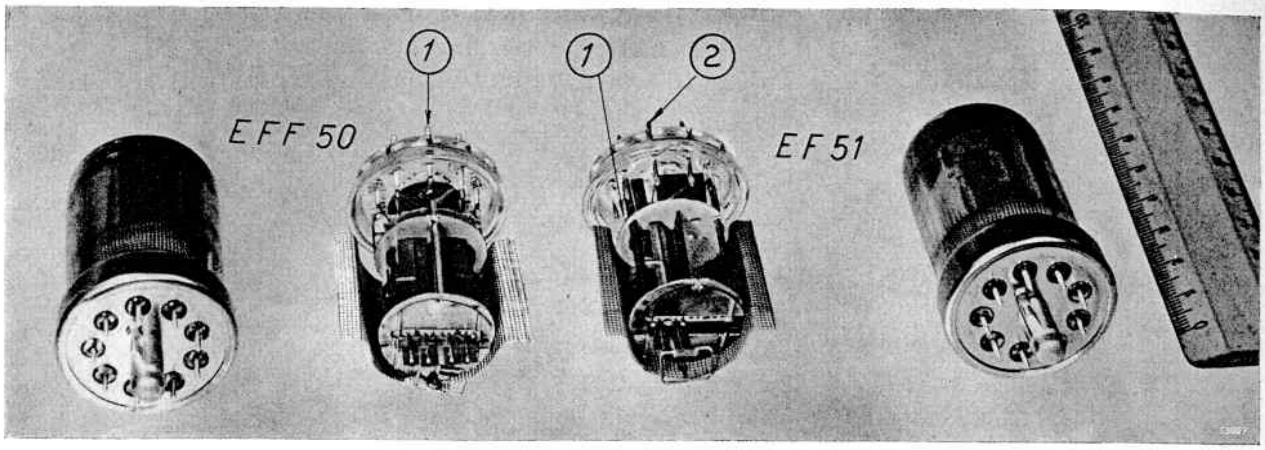

Fig. 4. Exterior and interior of the push-pull amplifier valve EFF 50, and of the valve with double cathode connection EF 51. The interior, from which the gauze screen has been removed, is mounted unsymmetrically in the case of the valve EF 51; *1* and *2* are the two cathode connections. In the case of the valve EFF 50 two identical systems are placed side-by-side and connected to a common cathode connection (*1*).

Construction of the amplifier valve with double cathode connection

In designing the amplifier valve with double cathode connection an attempt was made to make the harmful effect of the self-induction of the cathode connection as small as possible, even without the measures previously discussed. For this purpose the cathode connections, and particularly the first cathode connection, were kept extremely short, which could be done without changing the relative arrangement of the pins in the valve by placing the system unsymmetrically in the bulb, so that one end of the cathode falls exactly above the pin of the first cathode connection.

The construction of the valve with double cathode connection, type EF 51, is given in *fig. 4*. It may be seen that the appearance of this valve corresponds somewhat to that of the push-pull amplifier valve EFF 50 which is shown for the sake of comparison. In the case of the valve EF 51 the two cathode connections marked by arrows *1* and *2* may be distinguished; in the case of the push-pull amplifier valve, on the other hand, the two systems have a common cathode connection which is indicated by *1* in the photograph of the internal system.

The control grid of the valve EF 51, contrary to the case with EFF 50, has an irregular pitch (see *fig. 5*). In this way the magnitude of the negative control grid voltage, which is necessary to suppress the anode current, is made different for different parts of the cathode. In *fig. 6* it may be seen what effects this has on the characteristic. In the case of the valve EFF 50 the anode current is practically entirely suppressed by a control grid voltage of -6 V, and slightly above this "cut off voltage" the slope of the I_a-V_g characteristic (slope S_1 in fig. 6) decreases very sharply with falling control grid voltage. In the valve EF 51, on the other hand, the cut off voltage is different from point to point, in other words, the cutting off takes place quite gradually. The result is that the change in the slope also takes place quite gradually. Thanks to this property of the EF 51 it is possible to regulate the amplification of the valve by changing the grid bias, without experiencing much difficulty with non-linear distortion.

Fig. 5. *a*) Regular (*b*) irregular pitch of the control grid. For a control grid voltage in the regulation region the emission of the cathode is suppressed locally in the case of the irregularly wound grid.

The non-linear distortion is characterized in fig. 6 by the quotient S_3/S_1. The coefficients S_1 and S_3 are thereby derived from the series:

$$S = S_1 + S_2 (V_g - V_{g0}) + S_3 (V_g - V_{g0})^2 + \dots$$

which represents the behaviour of the slope S in the neighbourhood of the operating point (grid voltage V_{g0}). The strength of the cross modulation and of certain other undesired phenomena is found to be directly proportional to S_3/S_1 [4]), so that it is desirable to have this quotient as small as possible. As may be seen in fig. 6, S_3/S_1, in the case of the

[4]) On this subject we refer the reader to the book: Moderne Mehrgitter-Elektronenröhren, by M. J. O. Strutt, Springer (Berlin), 2nd edition 1939, p. 17.

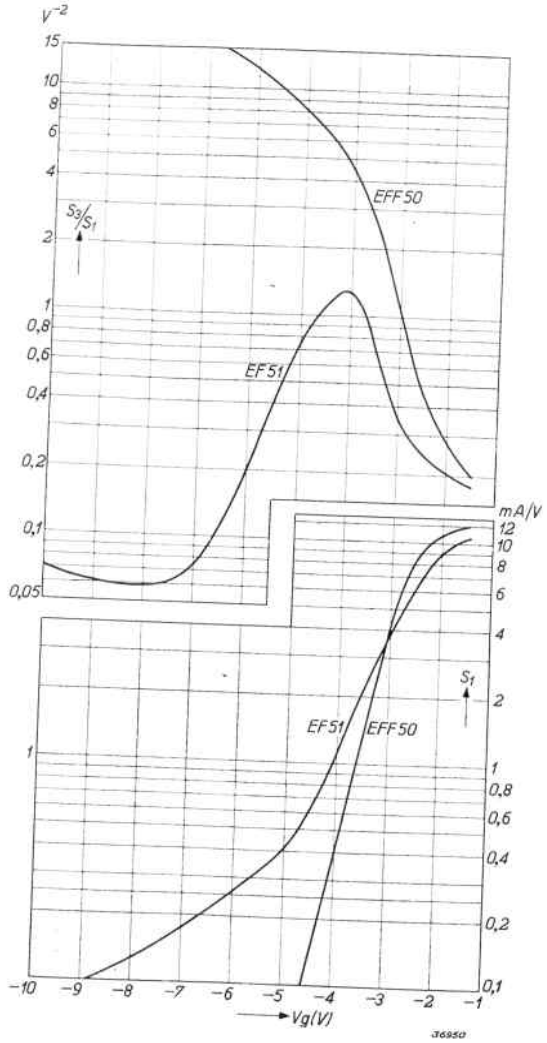

Fig. 6. Slope S_1 and distortion factor S_3/S_1 as a function of the grid voltage for the push-pull amplifier valve EFF 50 and for the valve with double cathode connection EF 51. The factor S_3/S_1 in the case of the valve EF 51, especially for large negative control grid voltages, is much smaller than in the valve EFF 50.

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Like all amplifier valves, the valve EF 51 exhibits a change in the input capacity upon regulation. This capacity variation may be unfavourable since due to it a detuning of the input circuit occurs. If only one cathode connection is used this capacity variation can for the most part be compensated in a simple way, for instance by the introduction of a resistance of about 30 ohms in this cathode connection. If both cathode connections are used the connections undergo several additional alterations.

The screen grid of the valve with double cathode connection is wound with a lower pitch than that of the push-pull amplifier valve. By this means the static capacity between control grid and anode is reduced and the internal resistance enlarged, which means an improvement of the valve qualities especially for not very short waves. In the following table the most important properties of the button pentode, the push-pull amplifier valve and the new amplifier valve with double cathode connection are shown side-by-side.

Table I

Properties of amplifier valves for very short waves.

Valve type	Button pentode 4 672	Push-pull amplifier valve EFF 50	Valve with double cathode connection EF 51
Slope (mA/V)	1.4	11*	10
Noise resistance R_r (ohms)	8 000	600*	900
Damping resistance R_e for $\lambda = 3$ m (ohms)	18 000	2 700*	3 600
R_r/R_e	0.44	0.22	0.25
C_{ag} for low frequencies (pF)	< 0.007	< 0.02	< 0.006

*) Per system (the valve contains two identical systems).
**) By this is meant the input parallel resistance which is equivalent to the damping due to the transit time of the electrons between cathode and control grid.

The noise qualities of the different valves are characterized in the table by the ratio between the socalled noise resistance R_r and the damping resistance R_e which occurs at the input side of the amplifier valve due to the finite transit time of the electrons between cathode and control grid. This quantity R_r/R_e is found in many practical cases to determine the maximum attainable ratio between signal voltage and noise voltage. From table I we see that the valve EF 51, as far as noise is concerned, is almost as good as the valve EFF 50 and considerably better than the button pentode 4 672.

Application of the valve with double cathode connection

The amplifier valve with double cathode connection will be used in the first place for the amplification of ultra short waves to a lower limit of 1.5 metres. These waves are of great importance, for example for telephony with directional aerials and possibly for television; in addition these frequencies are encountered as intermediate-frequency in superheterodyne receivers for still shorter waves.

The connections of the amplifier valve with double cathode connection can be based upon the diagram given in fig. 2, for example. This scheme

[5]) The capacity C_1 in many cases need not be realized by a separate condenser, but can be obtained by using the capacity between control grid and screen grid present in the valve. For this it is necessary that the screen grid should be connected for high frequency to the end of the second cathode connection, as is the case in the connections given in fig. 7.

is valid only for high-frequency currents, and must still be supplemented by the connection lines necessary for obtaining the desired biases of the different electrodes. In this way a scheme is arrived at like *fig. 7*, the functioning of which will be clear after the discussion of fig. 2.

If an attempt is made to apply these connections to practical cases, difficulties are found to occur due to parasitic capacities. The oscillation circuit *LC* in the anode circuit usually has a fairly considerable capacity with respect to earth or with respect to the chassis, and this capacity is in parallel with the capacity C_2. We have seen that C_2 causes a reaction which need only be very small to eliminate the small negative reactance present. If C_2 becomes too great a positive reactance occurs which, like the negative reactance, may have unfavourable effects on the amplification, for instance, a tendency to oscillation [6]). Therefore with these connections it is necessary to reduce the parasitic capacity between the oscillating circuit and earth, which can be done by housing the oscillating circuit in a closed container connected to the second cathode connection, as indicated in the figure.

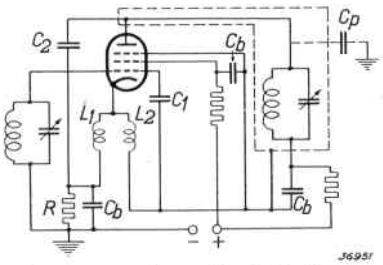

Fig. 7. Complete connections of a high-frequency amplifier stage with the valve EF 51 as amplifier valve. In order not to make the capacity C_2 too large due to the parasitic capacity C_p, the output circuit must be shielded. C_b block condensers. The resistance R serves to obtain the negative control grid bias.

If no other amplifier stage follows the connections just discussed, the method of shielding indicated can easily be realized. If, however, there are a number of stages in cascade, this is practically impossible. The anode A.C. voltage of the first valve must always be transmitted to the control grid of the following valve, which itself already possesses a capacity of about 10 pF with respect to earth.

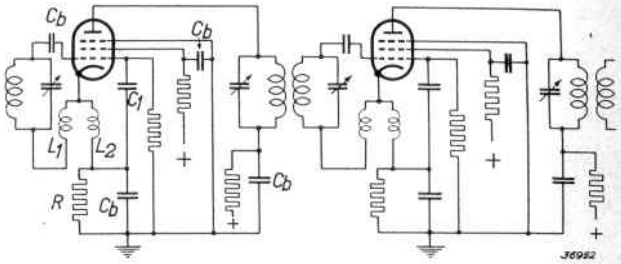

Fig. 8. Connections with the valve EF 51 in which no shielding of the output circuit is necessary. By inductive coupling any desired number of stages of this kind can be connected in succession. C_b block condensers. The resistance R serves for obtaining the negative control grid bias.

In order to be able to form cascade connections, therefore, it is desirable to use a connection with which no shielding of the anode circuit with respect to earth is necessary. Such a connection can be obtained very simply by connecting the second cathode connection in fig. 2, instead of the first, to earth. The scheme of connection thus obtained may be seen in *fig. 8*; it is also shown in this figure how by the use of an inductive coupling a second identical amplifier stage may be connected to the first stage. In this way any desired number of amplifier stages can be connected in succession. Instead of the magnetic coupling, electrostatic coupling can also be applied as shown in *fig. 9*. In this case two coupling condensers are required to take off the A.C. voltage to be transmitted from the two ends of the oscillation circuit. Apart from this the connections show no fundamental difference from the ordinary coupling with normal valves between successive stages.

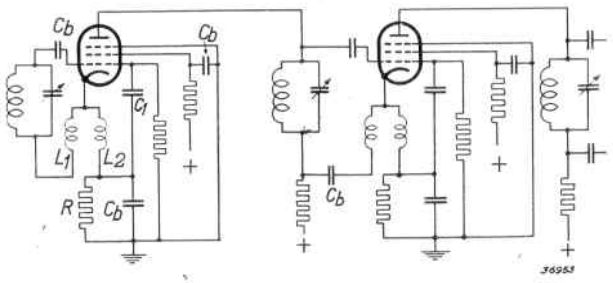

Fig. 9. Like fig. 8, but with a capacitative coupling between the stages.

[6]) On the disturbing effect of reactance see the article on transmitting pentodes, Philips techn. Rev. **2**, 257, 1937, especially fig. 3 and page 261.