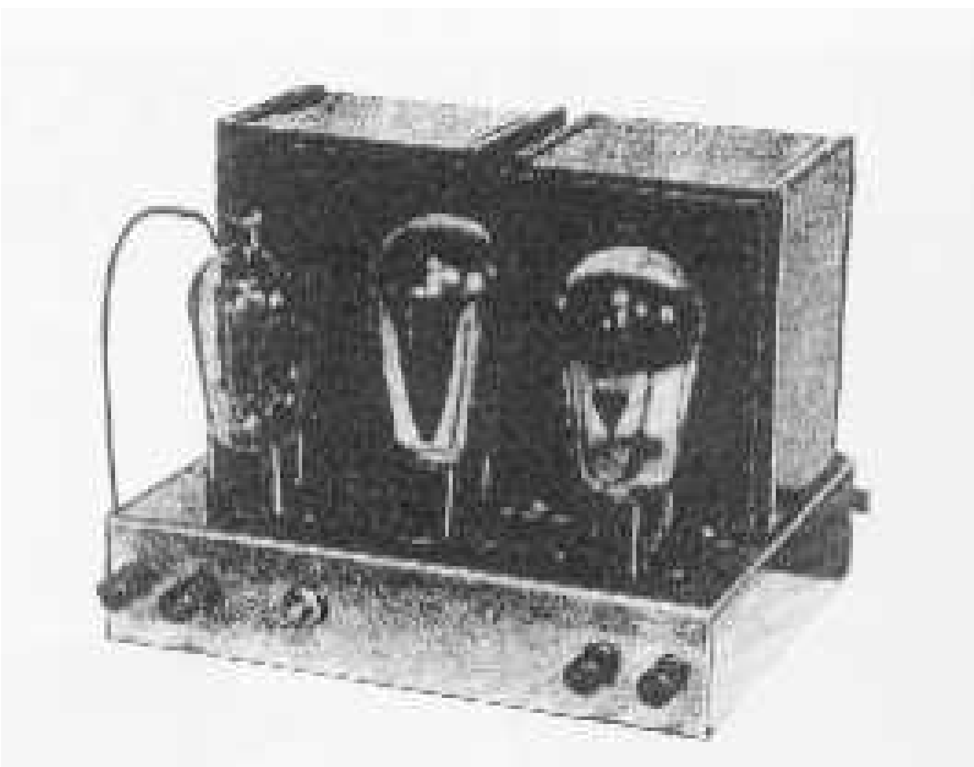
Audio Power Amplifiers

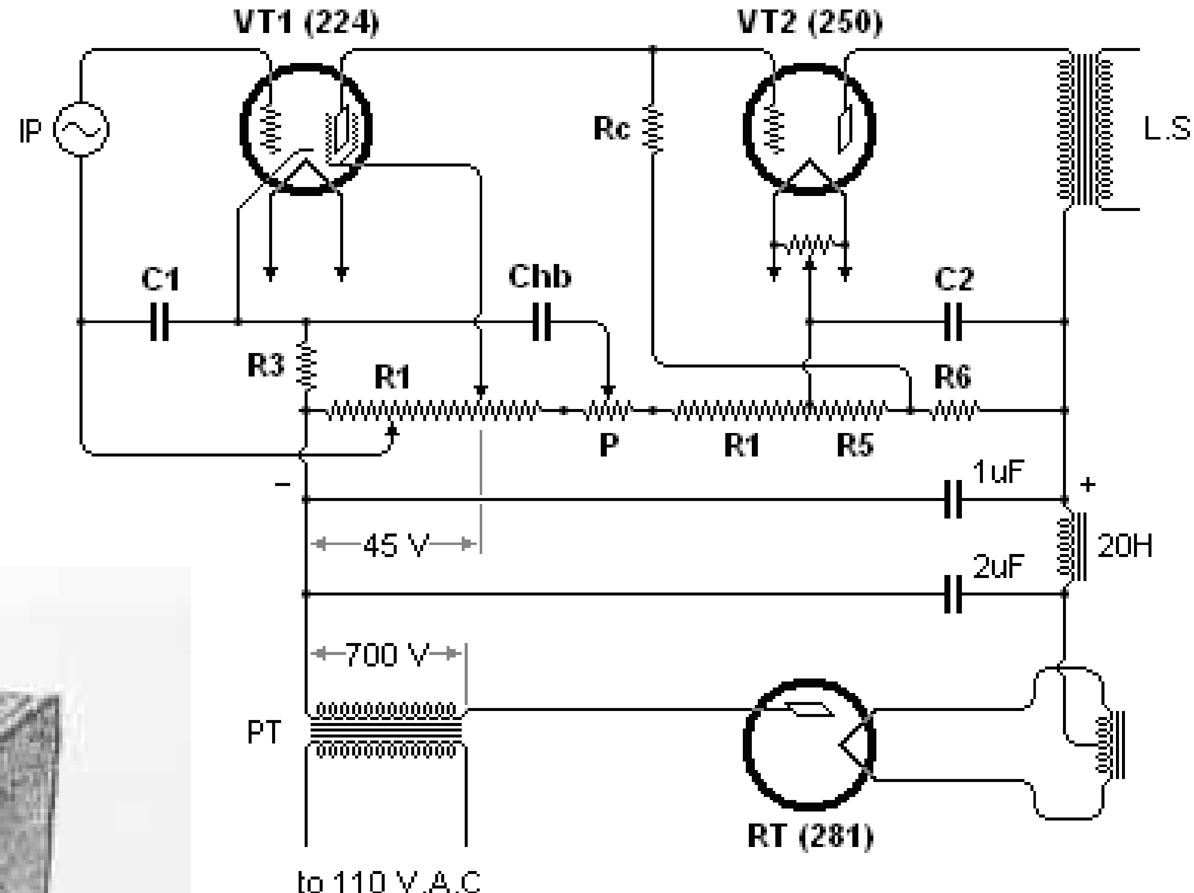
History and design of the audio amplifier

Graeme J Cohen AES Sept 25 2012

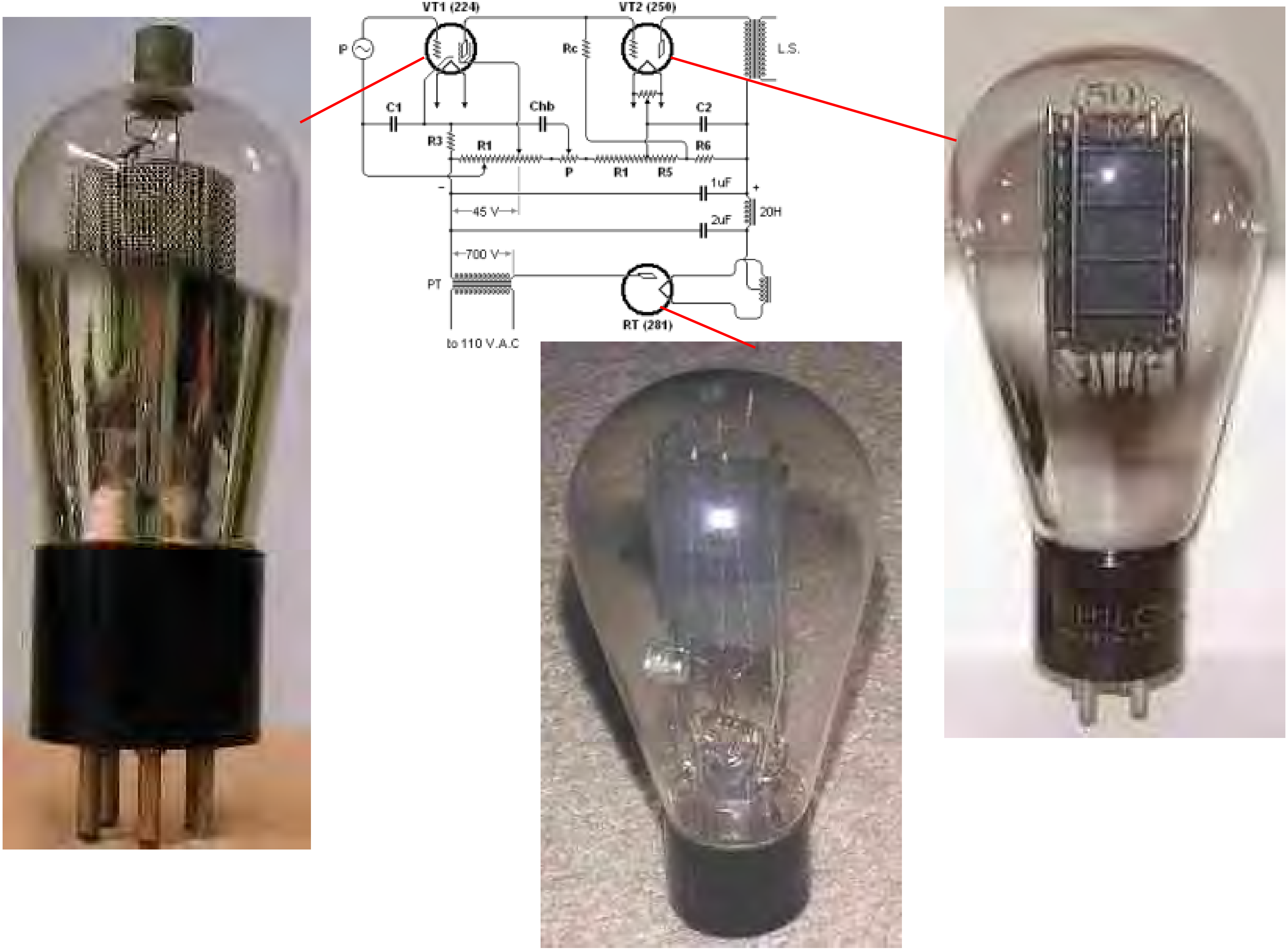
Early High Quality Sound

The Loftin-White amplifier





The Loftin-White circuit as it was published in Radio News issue January 1929


VT1 (224)
VT2 (250)
P
Rc
L.S.
C1
Chb
C2
R3
R1
R6
P
R1
R5
1uF
45 V
2uF
20H
700 V
PT
RT (281)
to 110 V.A.C

POWER OUTPUT SYSTEMS

A Paper delivered before the New South Wales Division of The Institution of Radio Engineers, Australia, at Science House, Sydney, on December 3, 1936.

by
F. Langford Smith*
B.Sc., B.E., M. Inst. R.E. (Aust.)

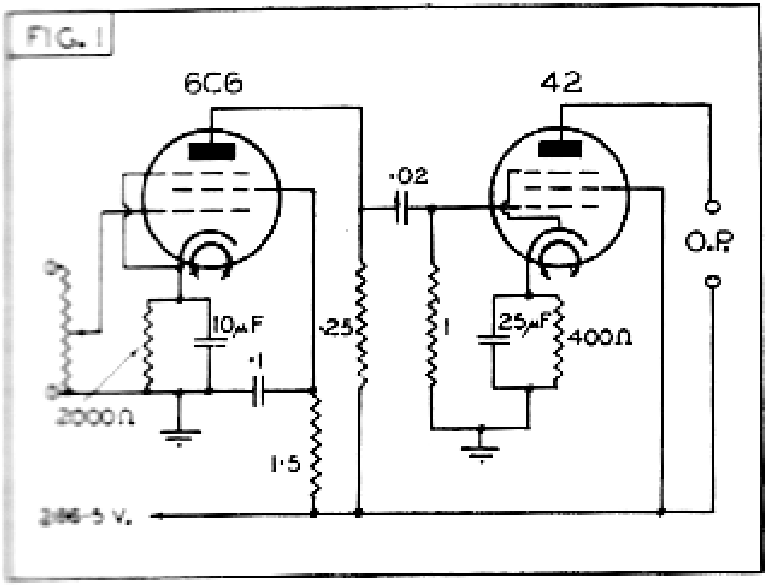


FIG. 1

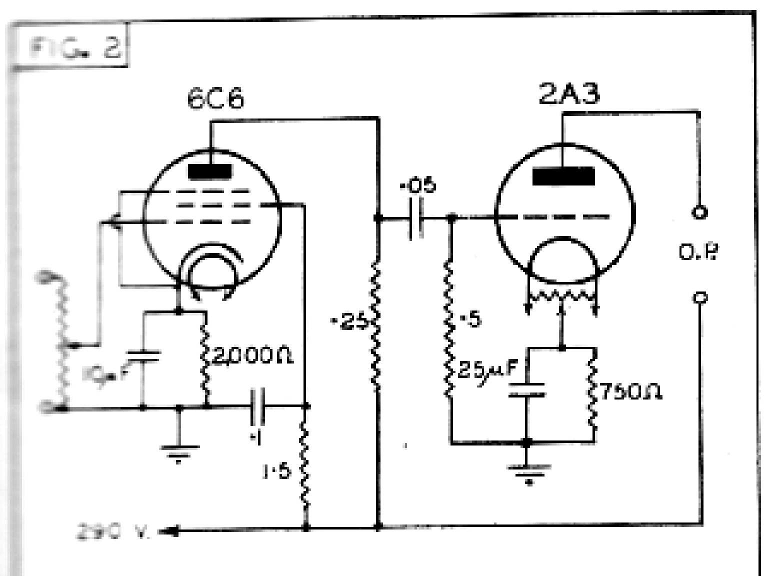


FIG. 2

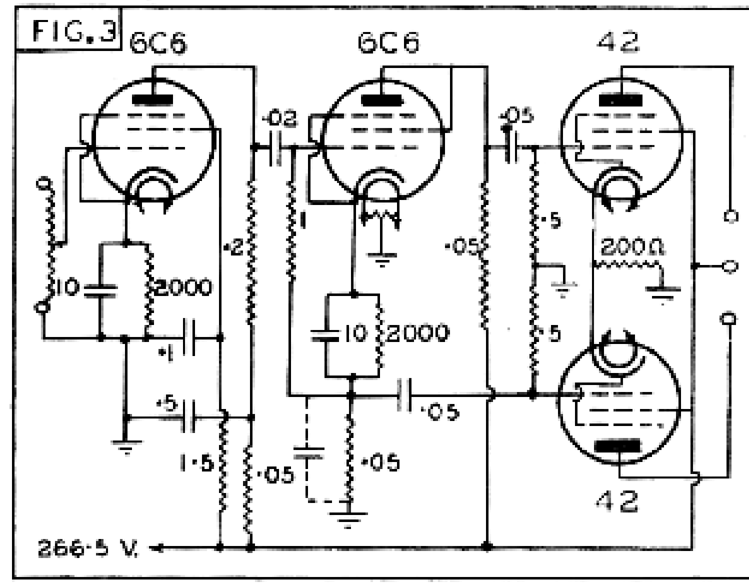


FIG. 3

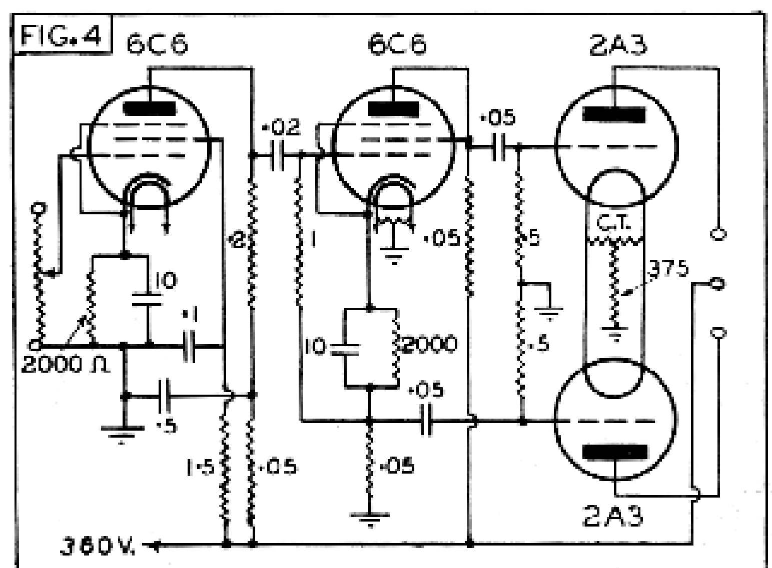
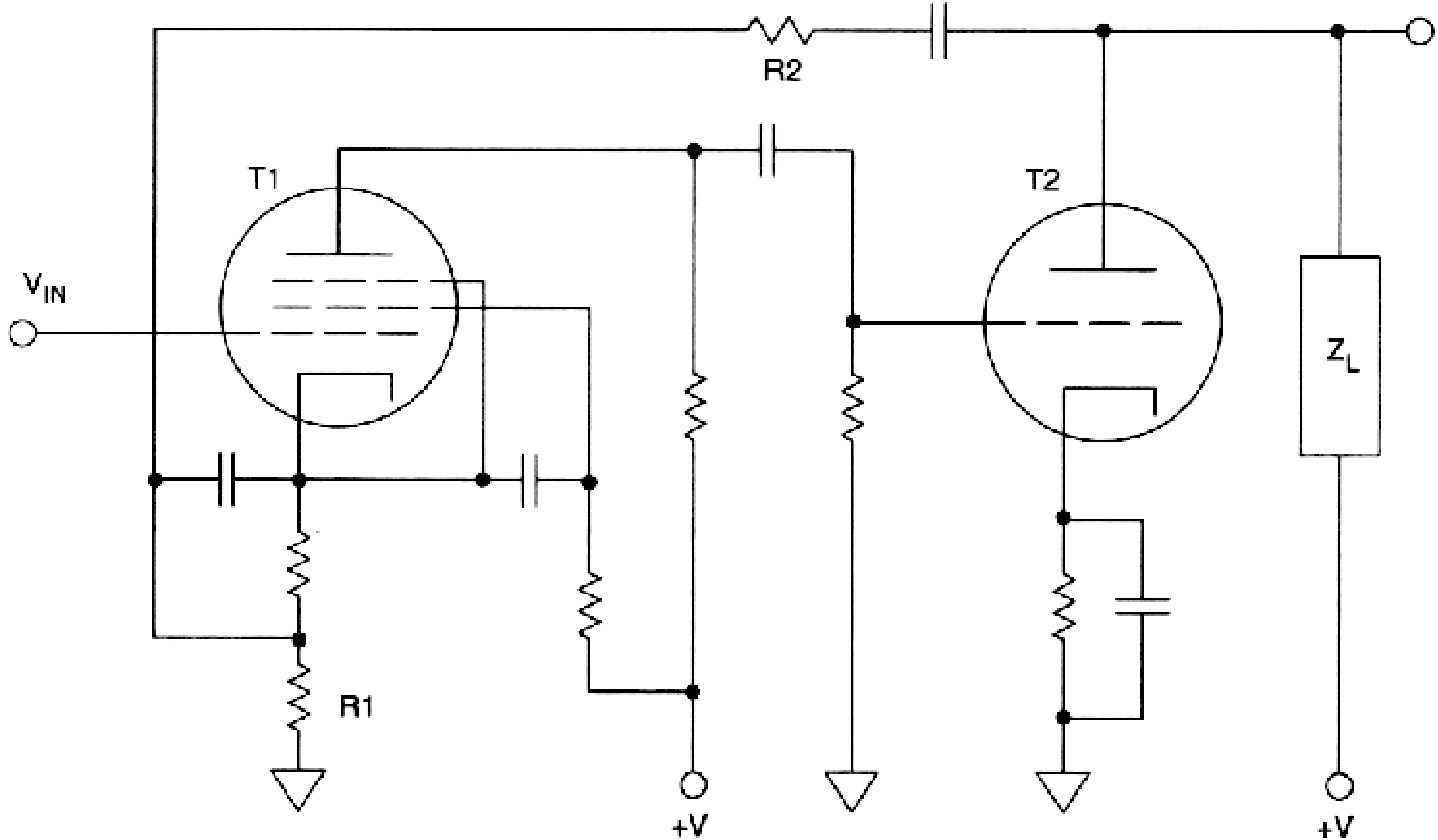
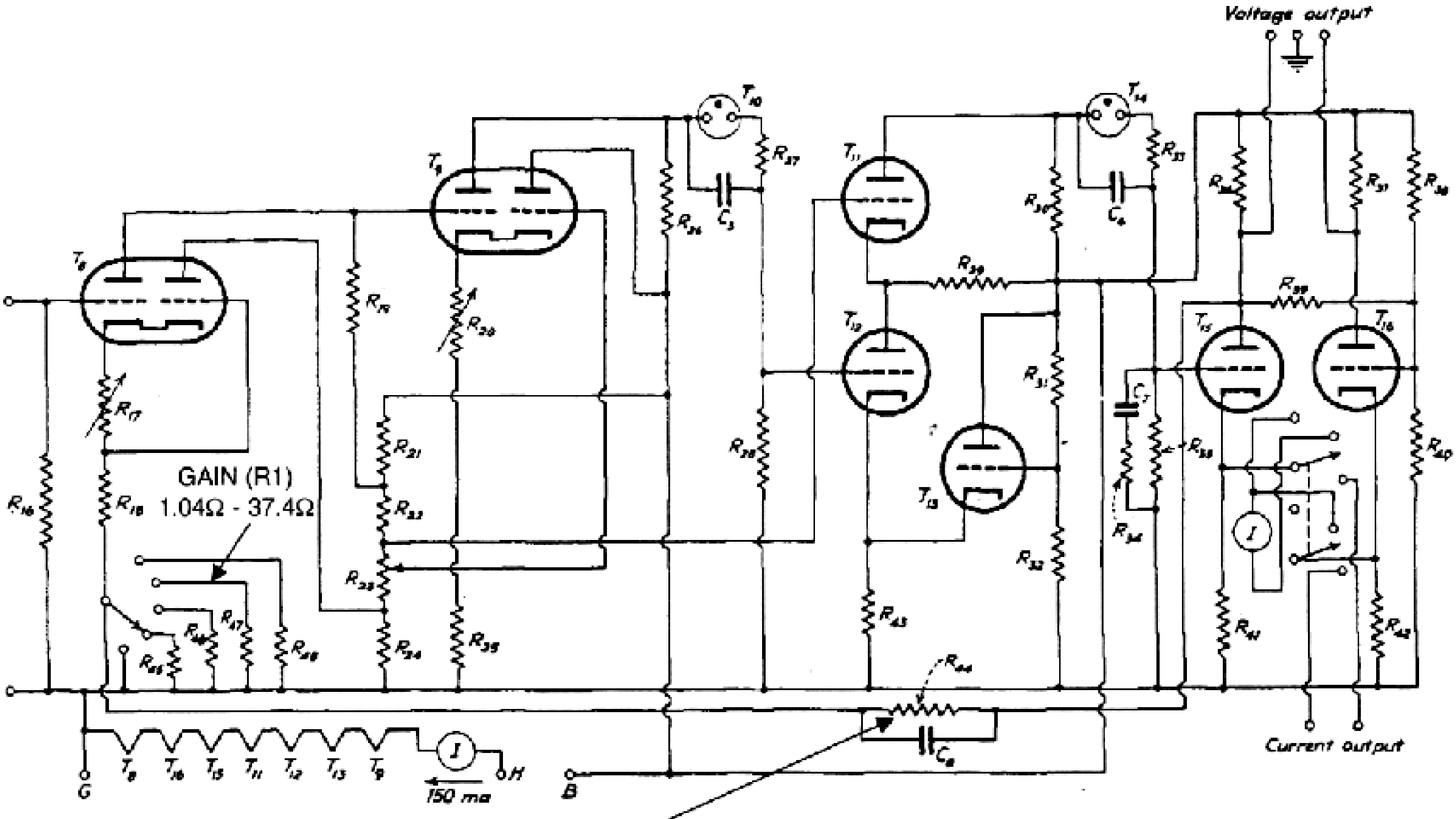


FIG. 4



Adapted from: Frederick E. Terman, "Feedback Amplifier Design," Electronics, January 1937, pp. 12-15, 50.

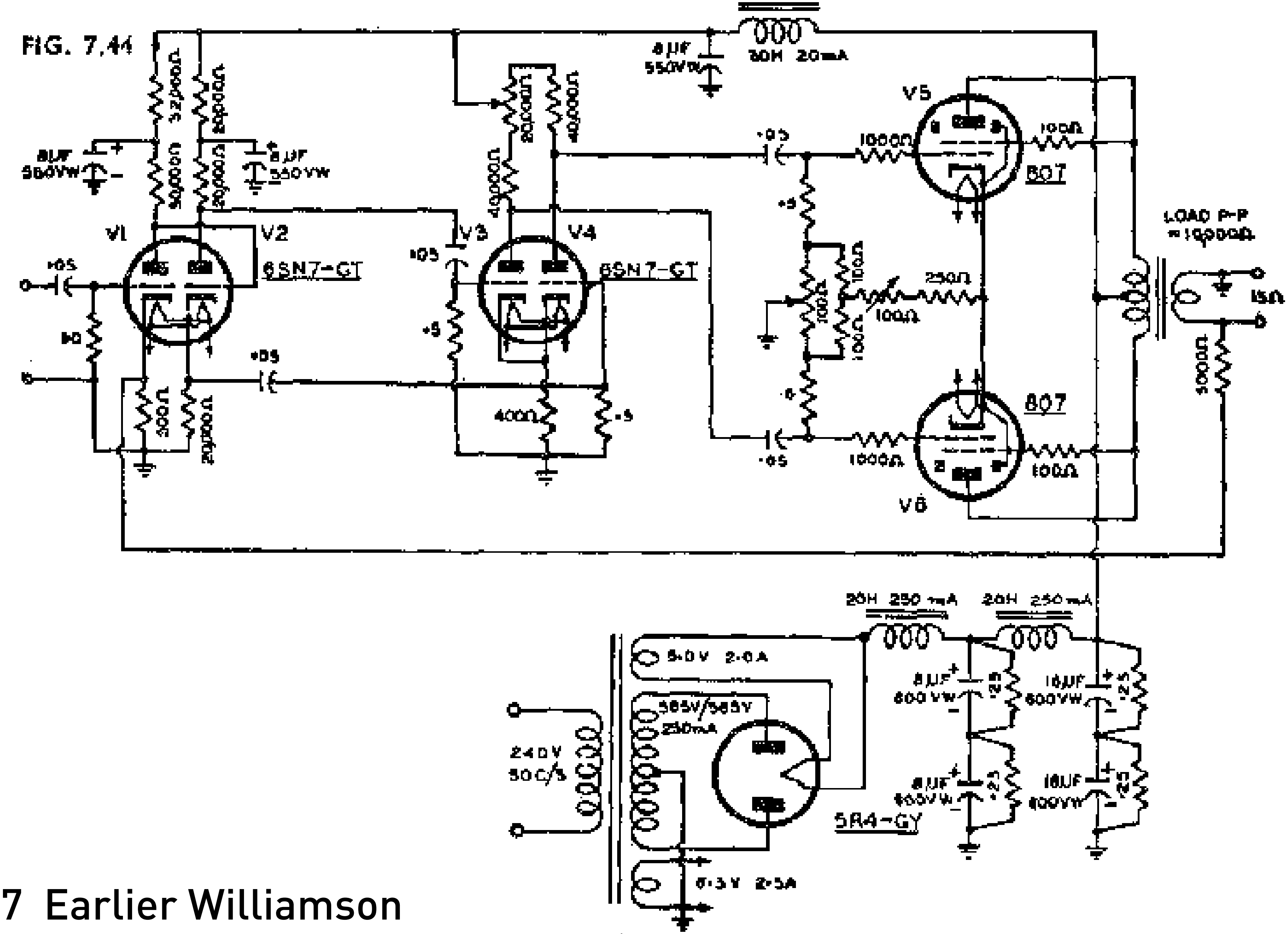
A 1937 vacuum tube feedback circuit designed by Frederick E. Terman, using current feedback to the low impedance input cathode (adapted from Reference 2)



Adapted from: Stewart E. Miller, "Sensitive DC Amplifier with AC Operation," Electronics, November 1941, pp. 27–31, 105–109

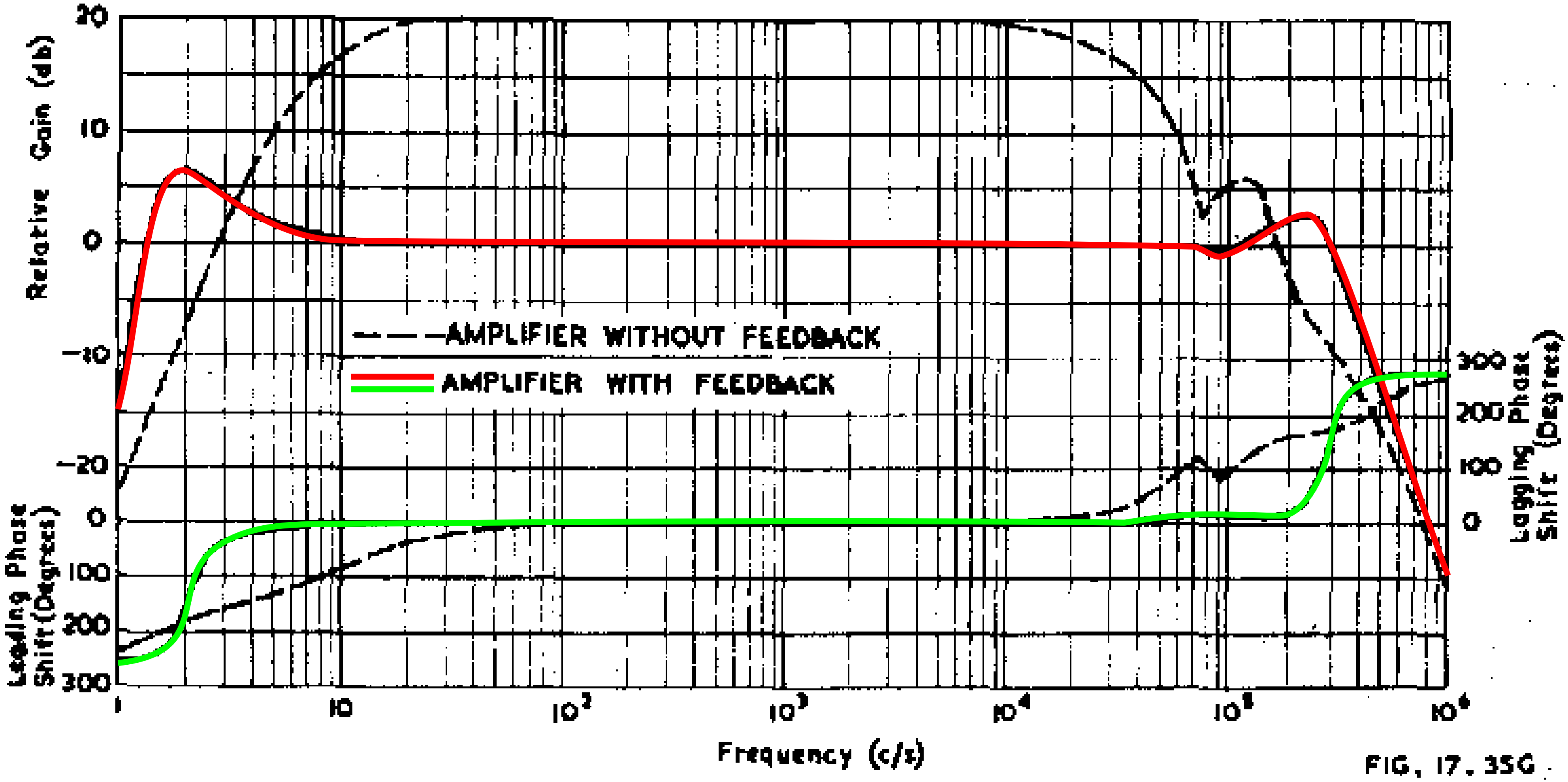
A 1941 vacuum tube feedback circuit using current feedback

FIG. 7.44



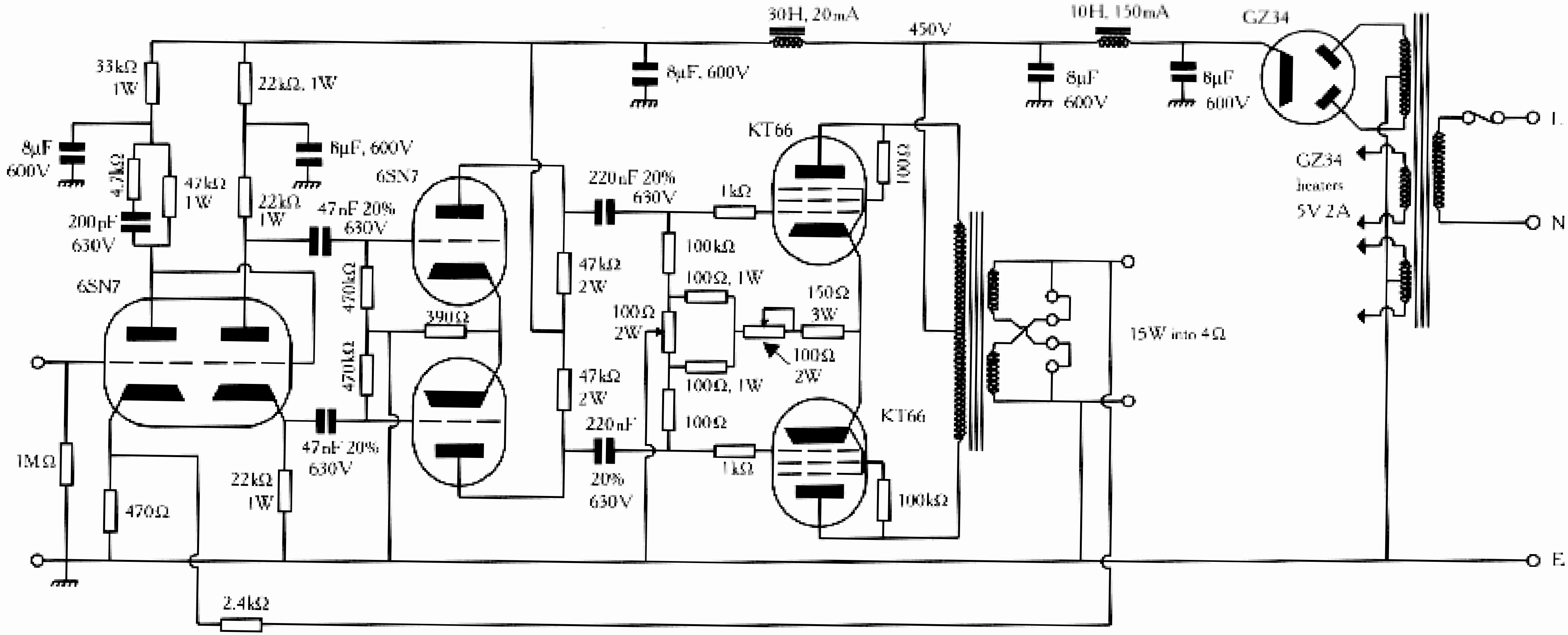
1947 Earlier Williamson

Amplifier employing voltage feedback from the secondary of the output transformer, with push-pull triodes. The amplifier is virtually distortionless up to an output of 11 watts, and has a smooth overload up to 16 watts.

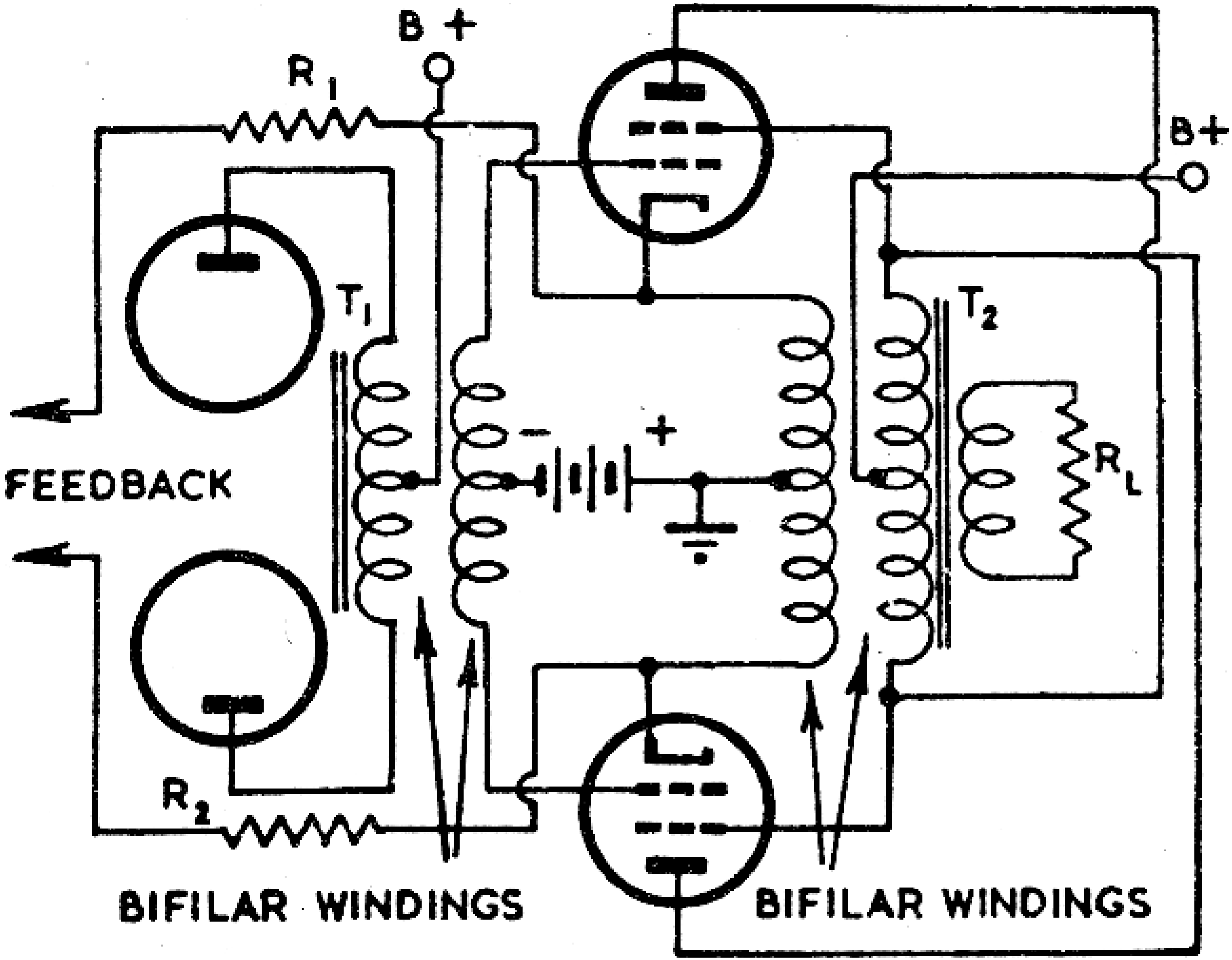


Loop gain and phase-shift characteristics of Williamson main amplifier

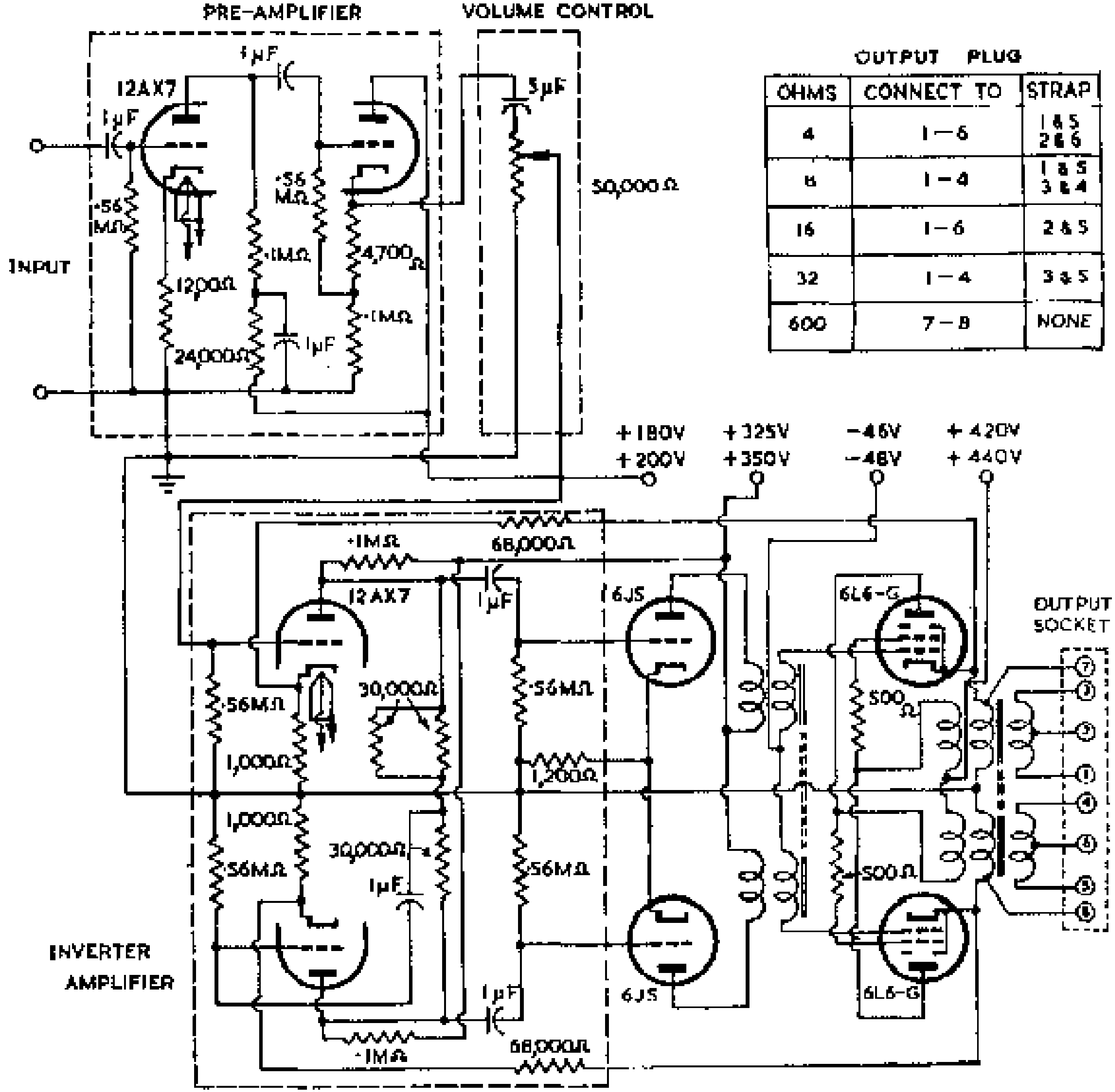
1947 Earlier Williamson. Loop gain and phase.



1949 Williamson amplifier



1949 Basic principles of McIntosh Amplifier

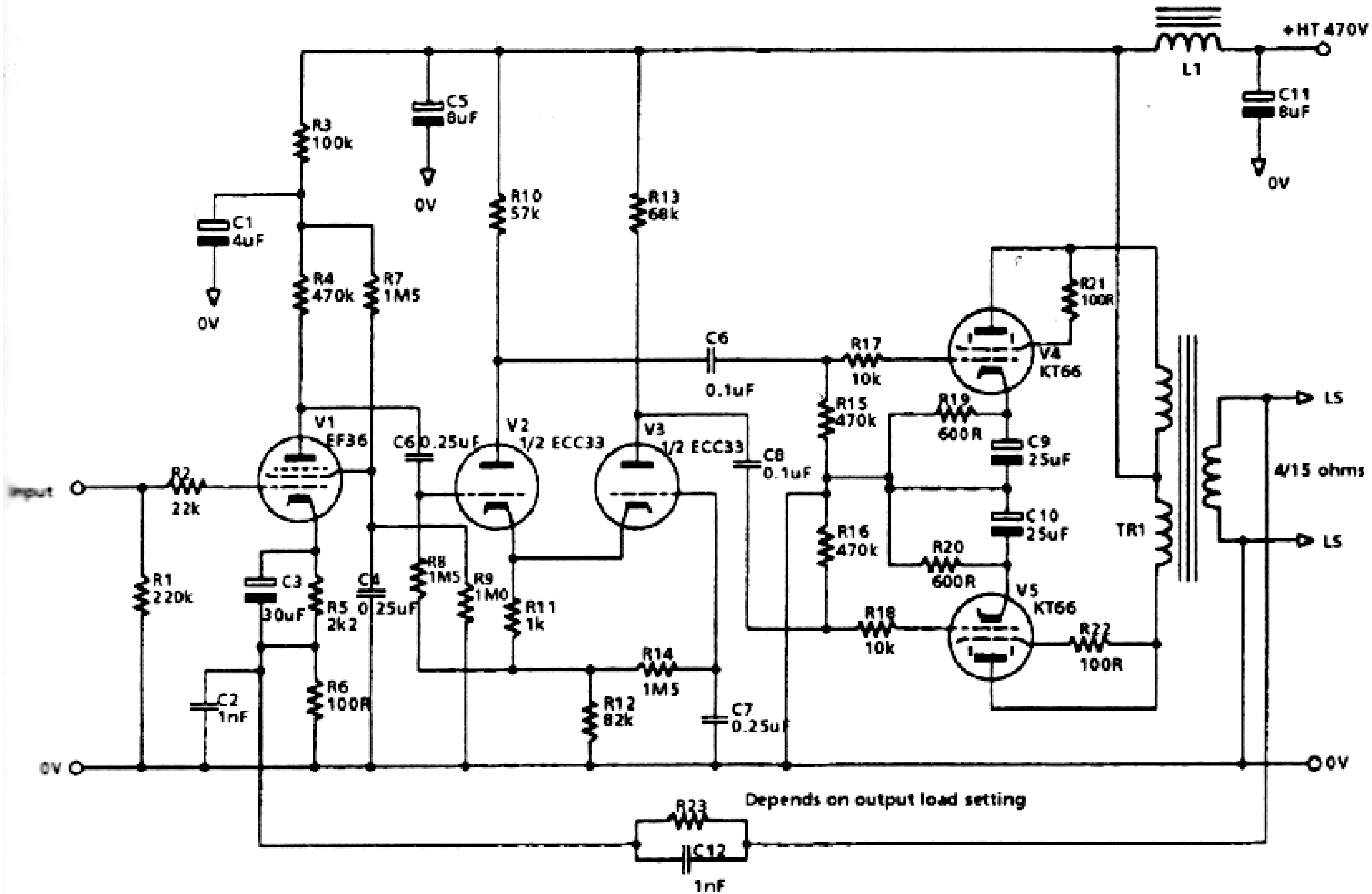


OUTPUT PLUG

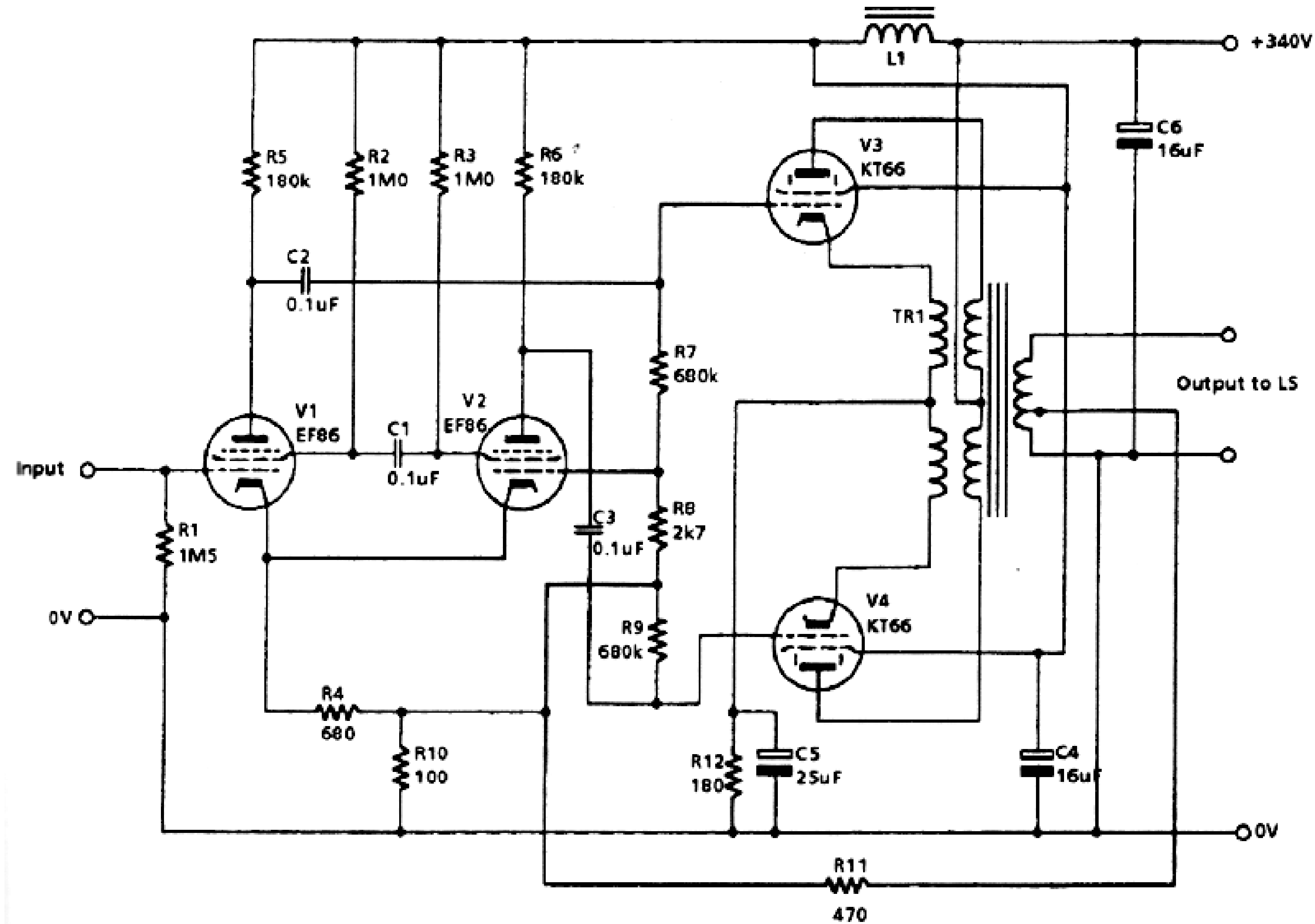
OHMS	CONNECT TO	STRAP
4	1 — 6	1 & 5 2 & 6
8	1 — 4	1 & 5 3 & 4
16	1 — 6	2 & 5
32	1 — 4	3 & 5
600	7 — 8	NONE

1949 Complete 50 watt McIntosh amplifier

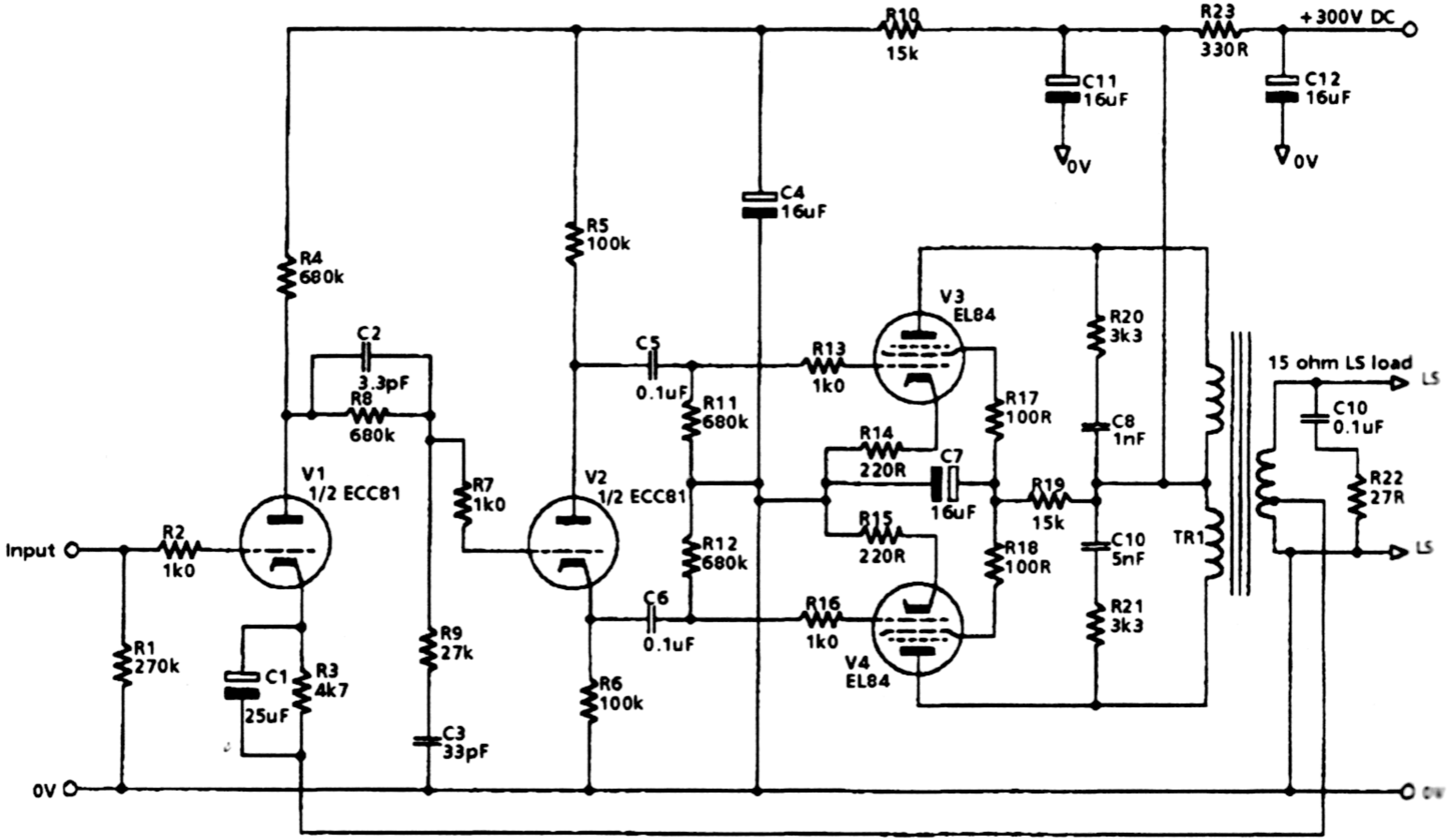
Quality Sound 1950s



1949 The Leak TL12



1952 The Quad amplifier



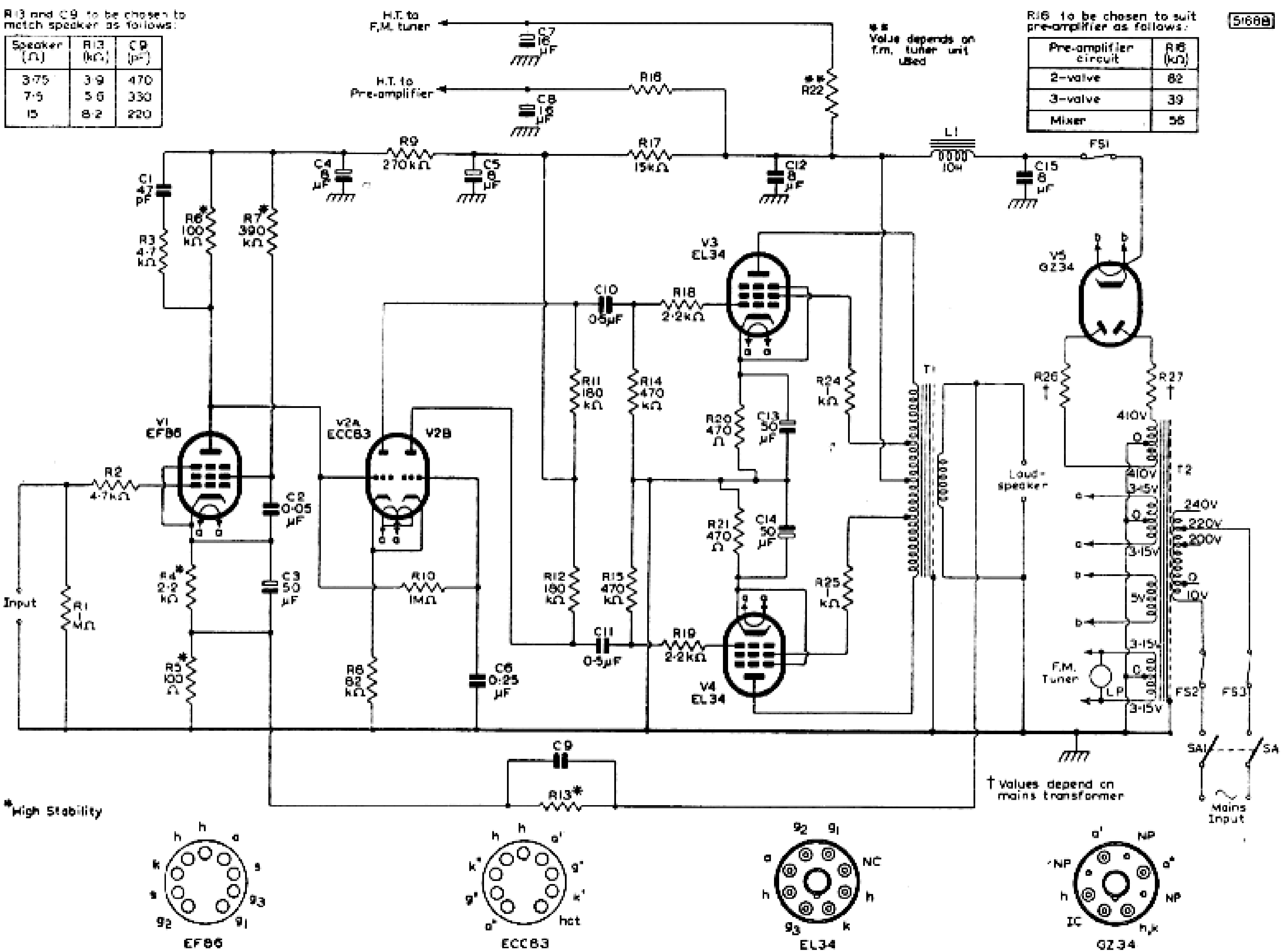
1957 Baxandall's simple amplifier

R13 and C9 to be chosen to match speaker as follows:

Speaker (Ω)	R13 (kΩ)	C9 (pF)
3·75	3·9	470
7·5	5·6	330
15	8·2	220

R16 to be chosen to suit pre-amplifier as follows:

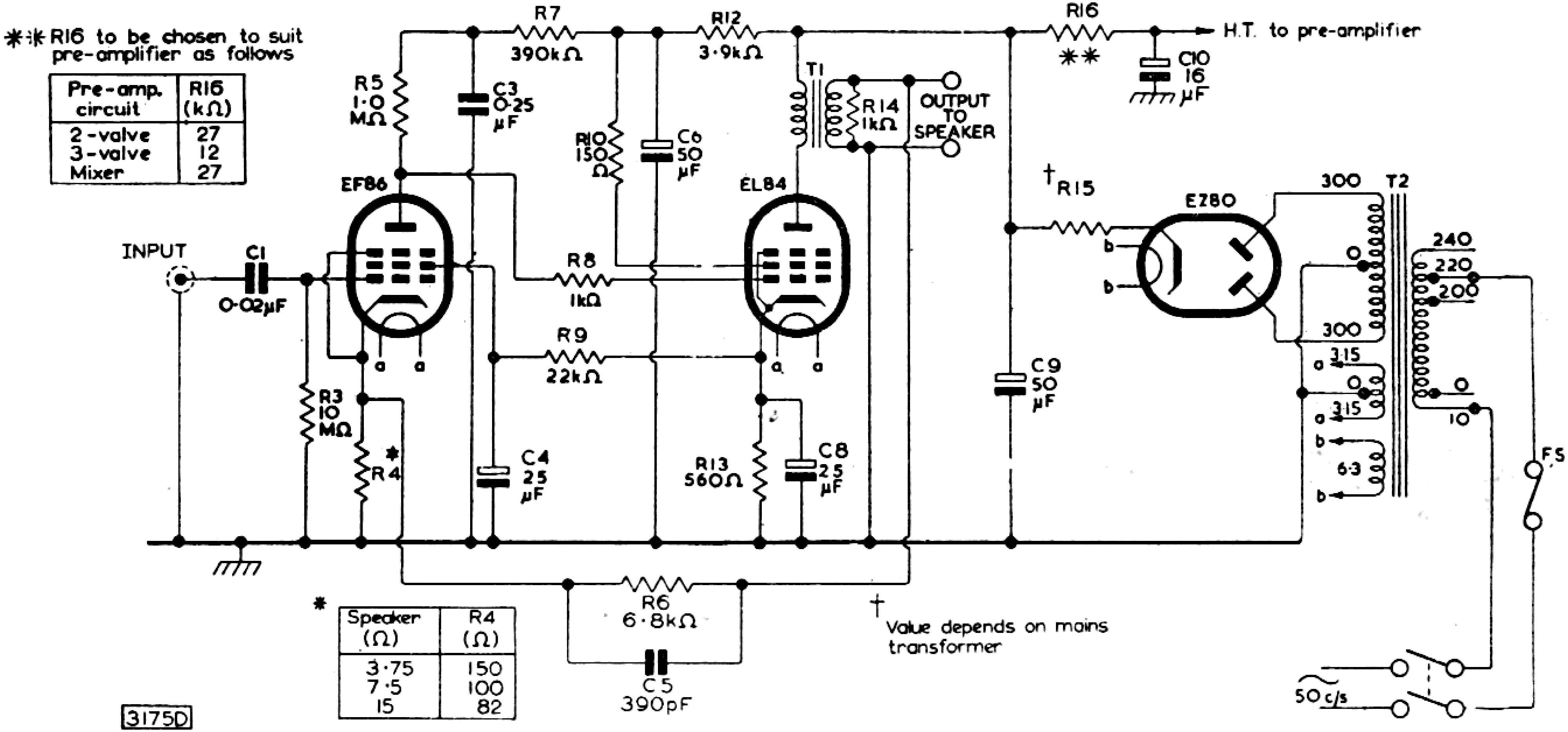
Pre-amplifier circuit	R16 (kΩ)
2-valve	82
3-valve	39
Mixer	56



Circa 1959 Mullard 20W amplifier

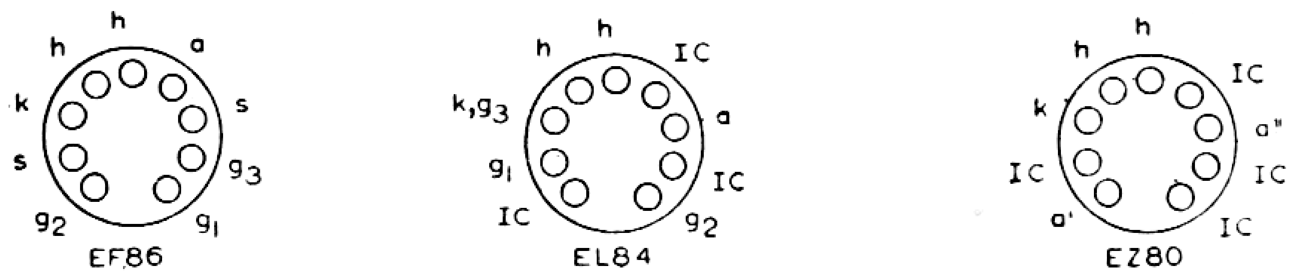
Comparison between Triode, Pentode and Distributed-load Operation of EL34s

Valve	Mode of Operation	Total Distortion (%)				
		10W	14W	20W	30W	40W
EL34	Triode connection	0·5	0·7	—	—	—
	Distributed load					
	(*a*) 20% common winding	0·7	0·8	1·0	1·5	5·0
	(*b*) 43% common winding	0·6	0·7	0·8	1·0	—
	Pentode connection	1·5	2·0	2·5	4·0	6·0

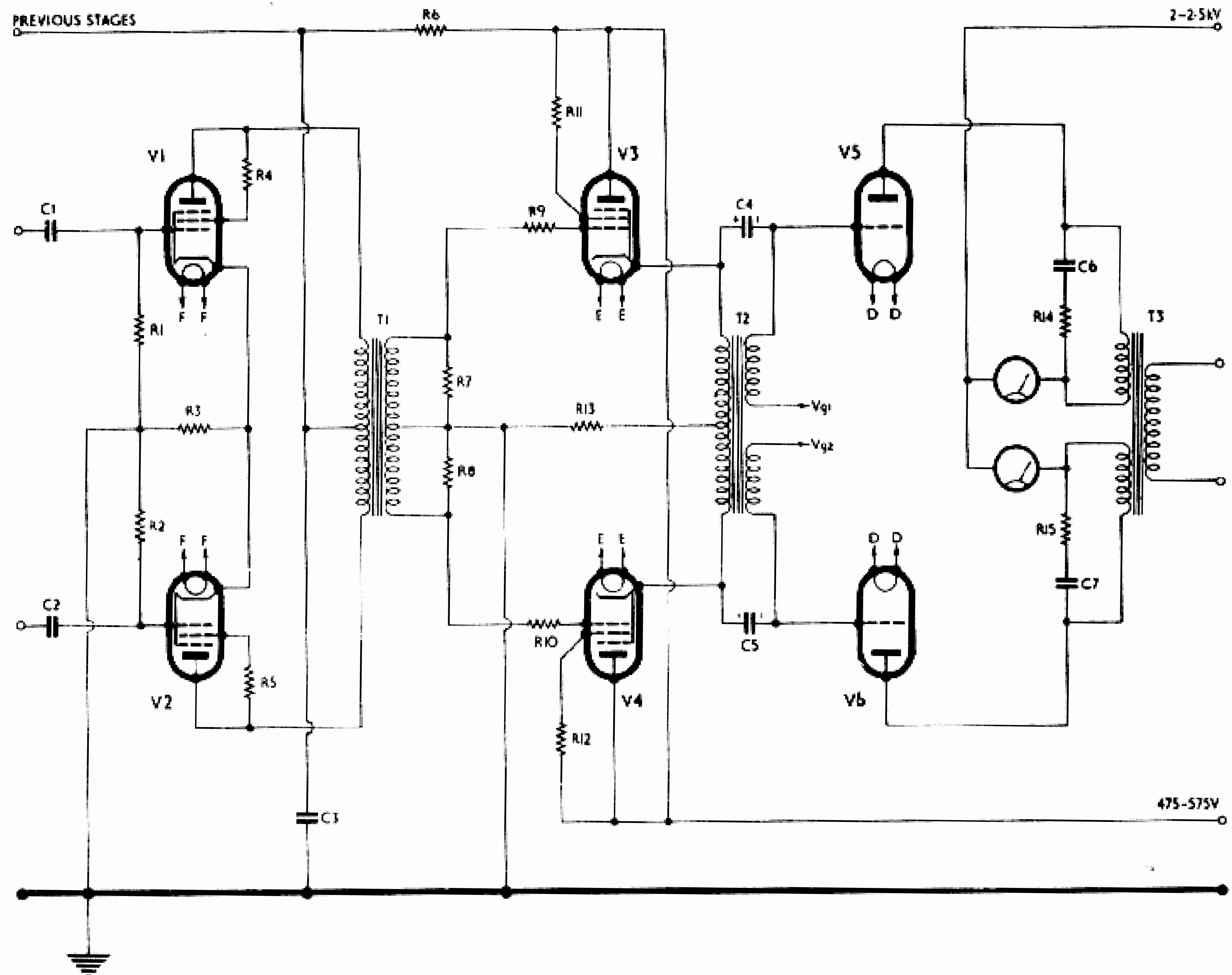


Pre-amp. circuit	R16 (kΩ)
2-valve	27
3-valve	12
Mixer	27

* Speaker (Ω)	R4 (Ω)
3·75	150
7·5	100
15	82



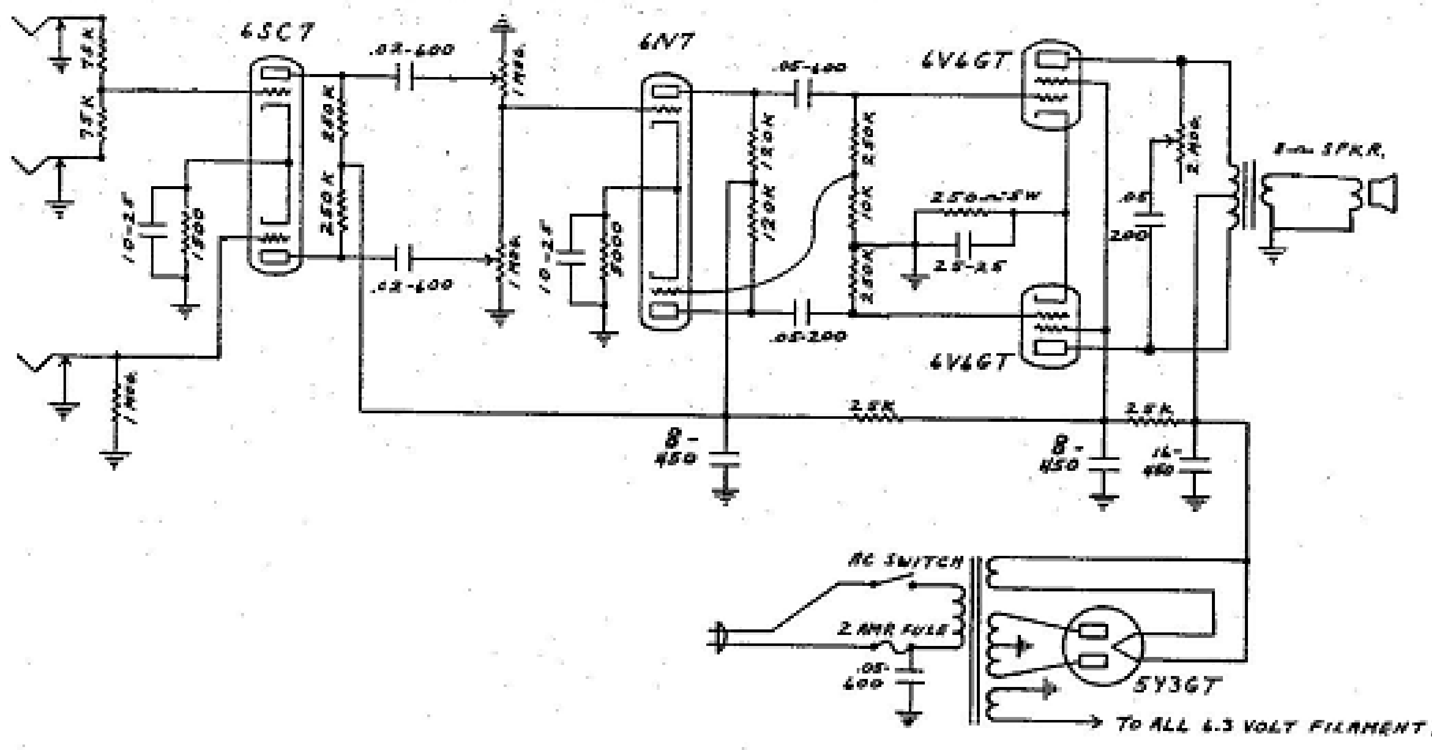
Circa 1959 Mullard 3-3 (3 valves and 3 watts)



Circa 1959 General Electric Class AB2 600-1100 watt amplifier.

Guitar Amplifiers

FENDER "DELUXE" SCHEMATIC
MODEL 26



"Woodies" 1946


Marshall
Marshall
Marshall
Marshall
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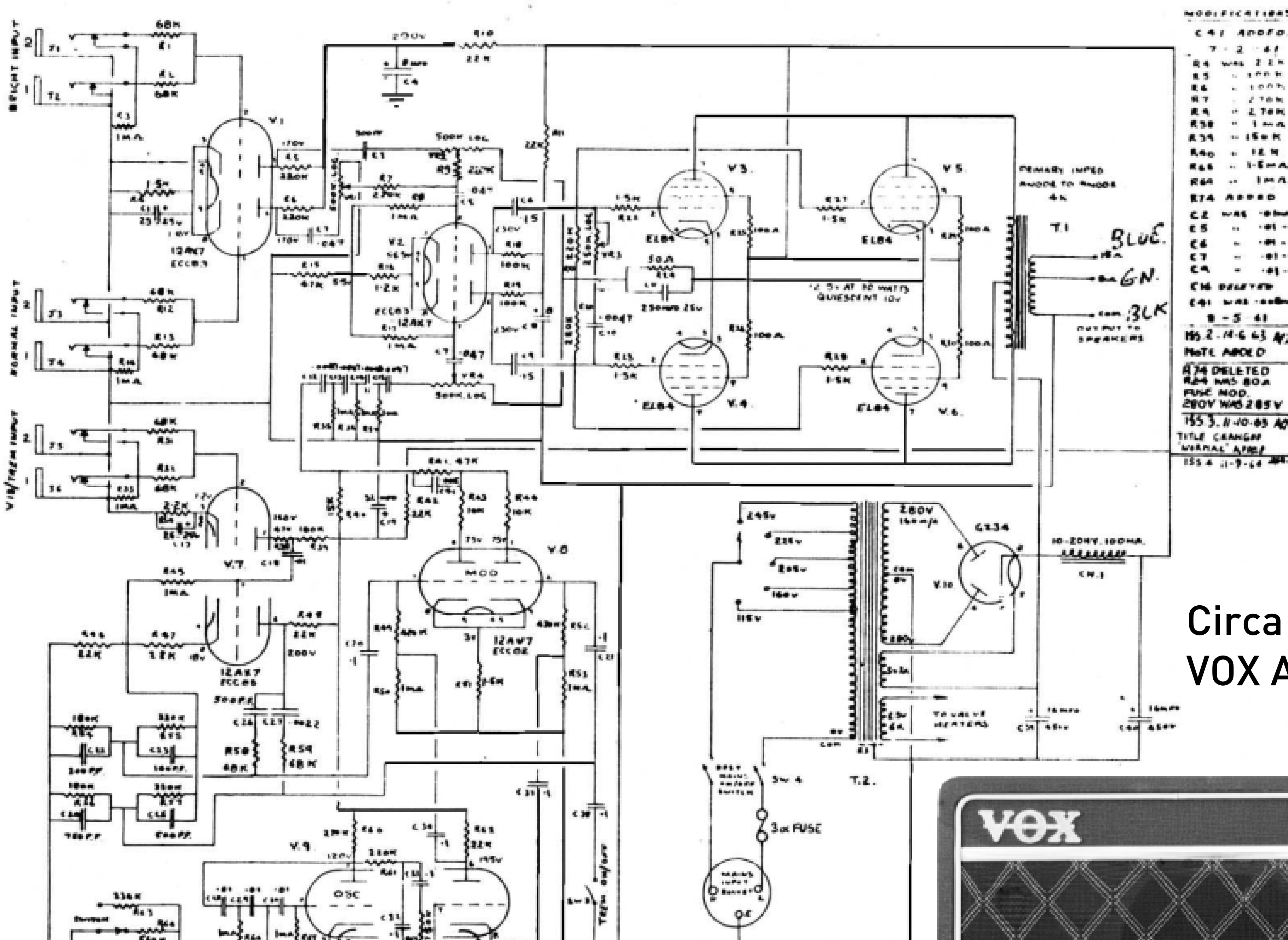
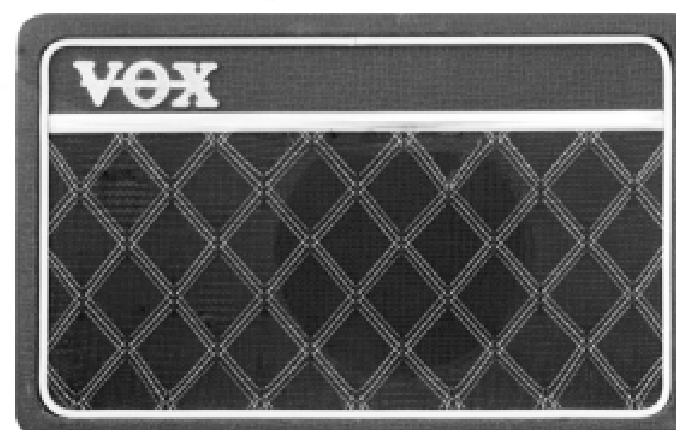
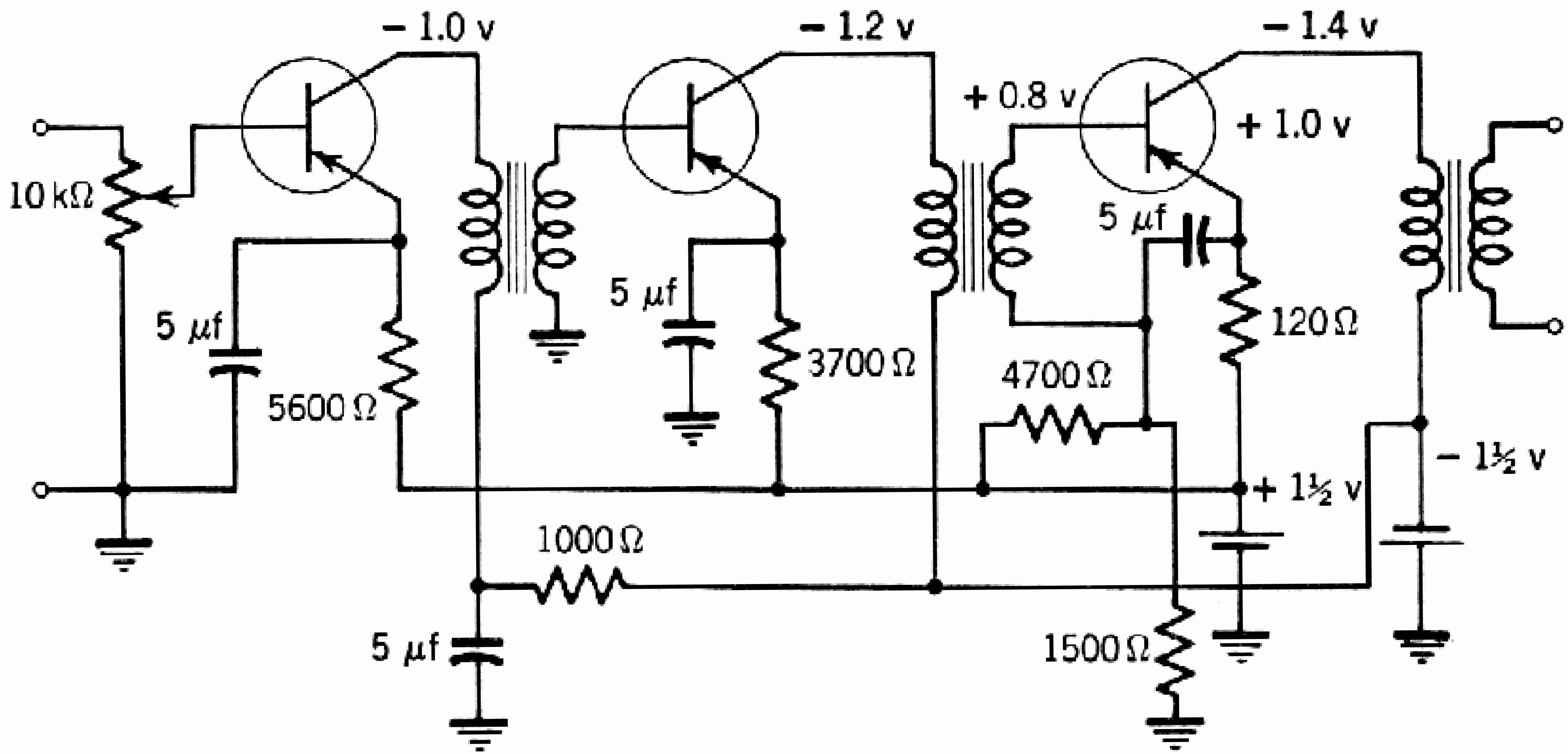
Circa 1950's



Circa 1950's
VOX AC30

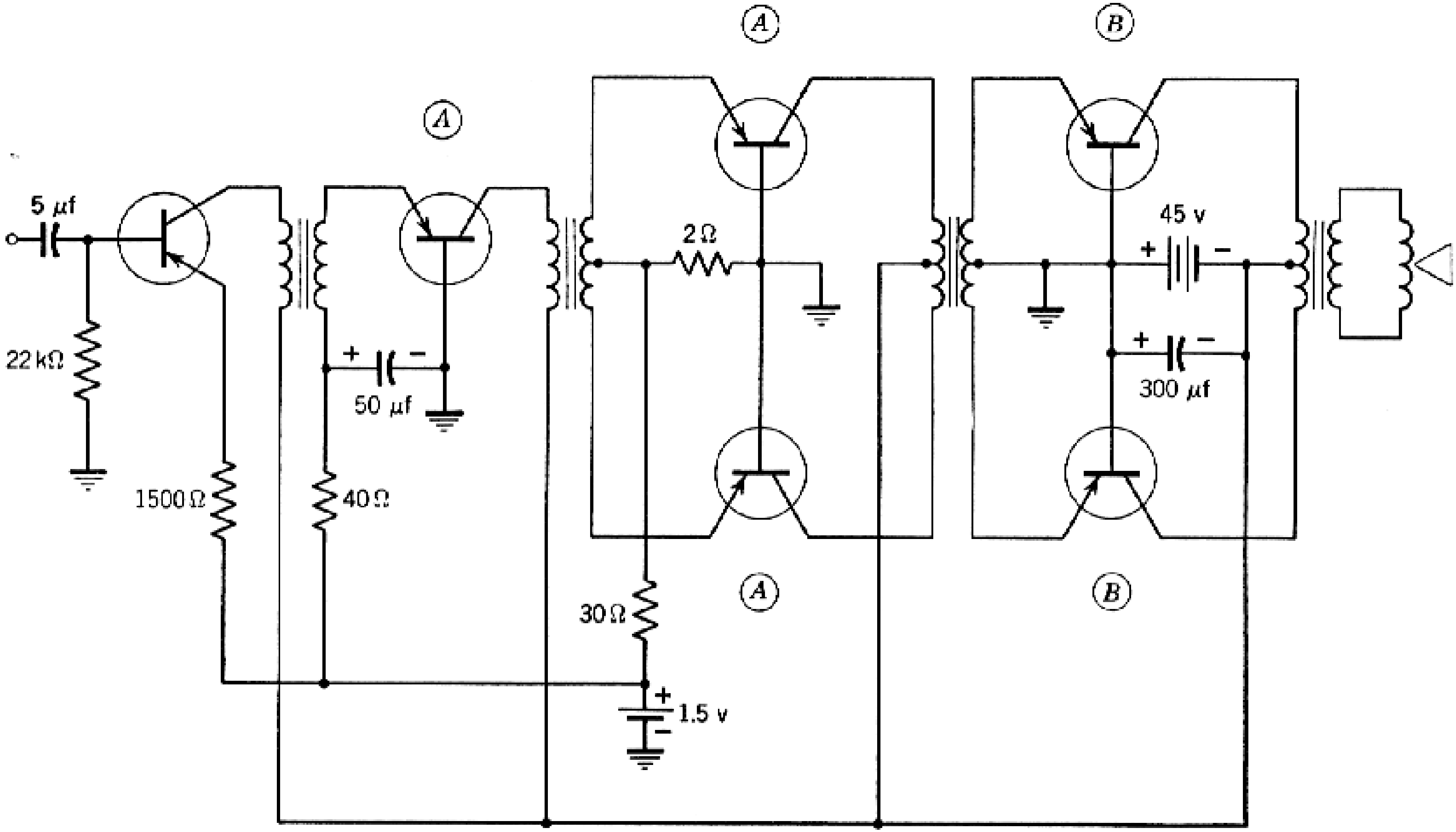


Early Solid State Amplifiers



Hearing-aid circuit.

Circa 1953

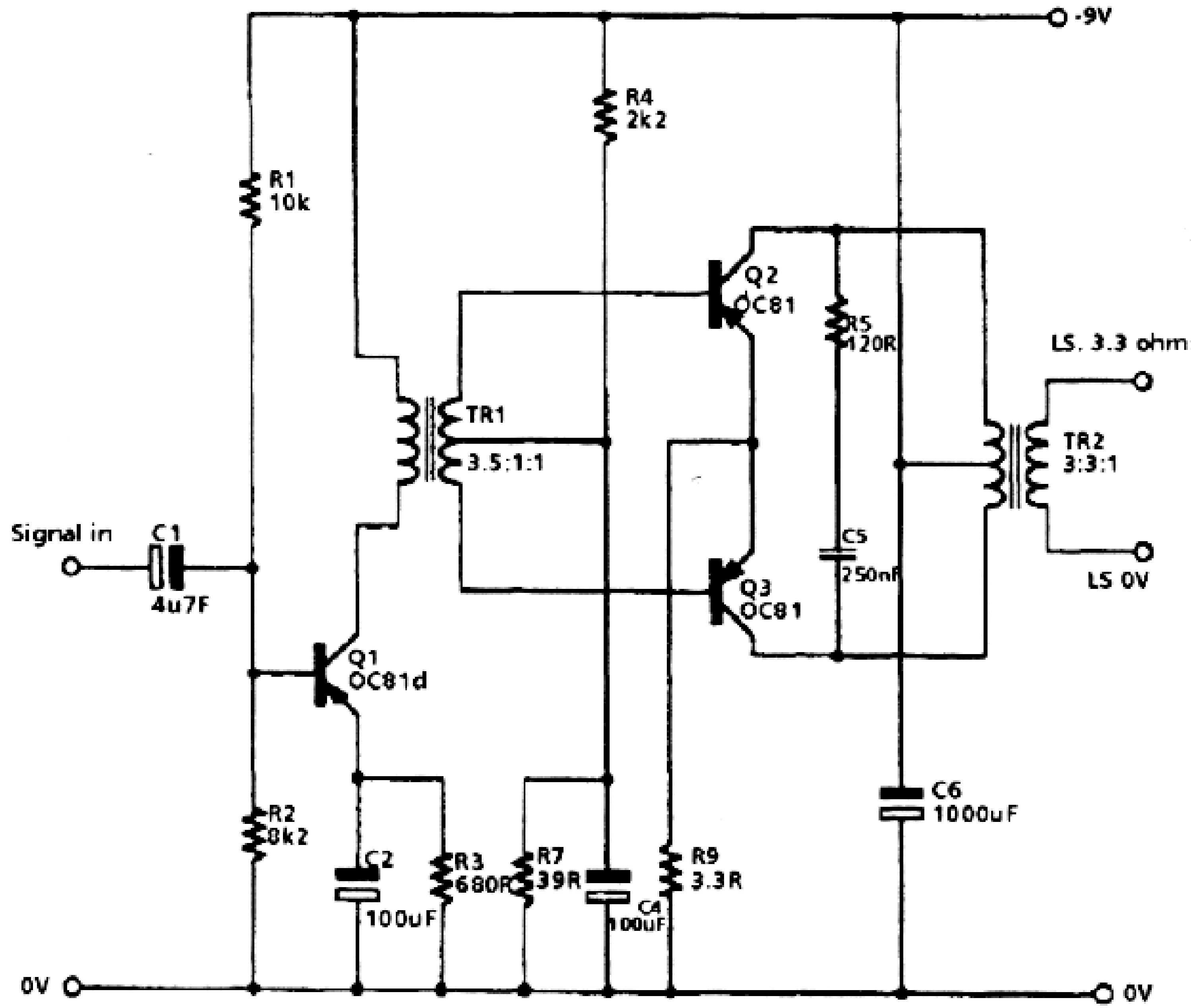


Ⓐ Special medium-power transistors.

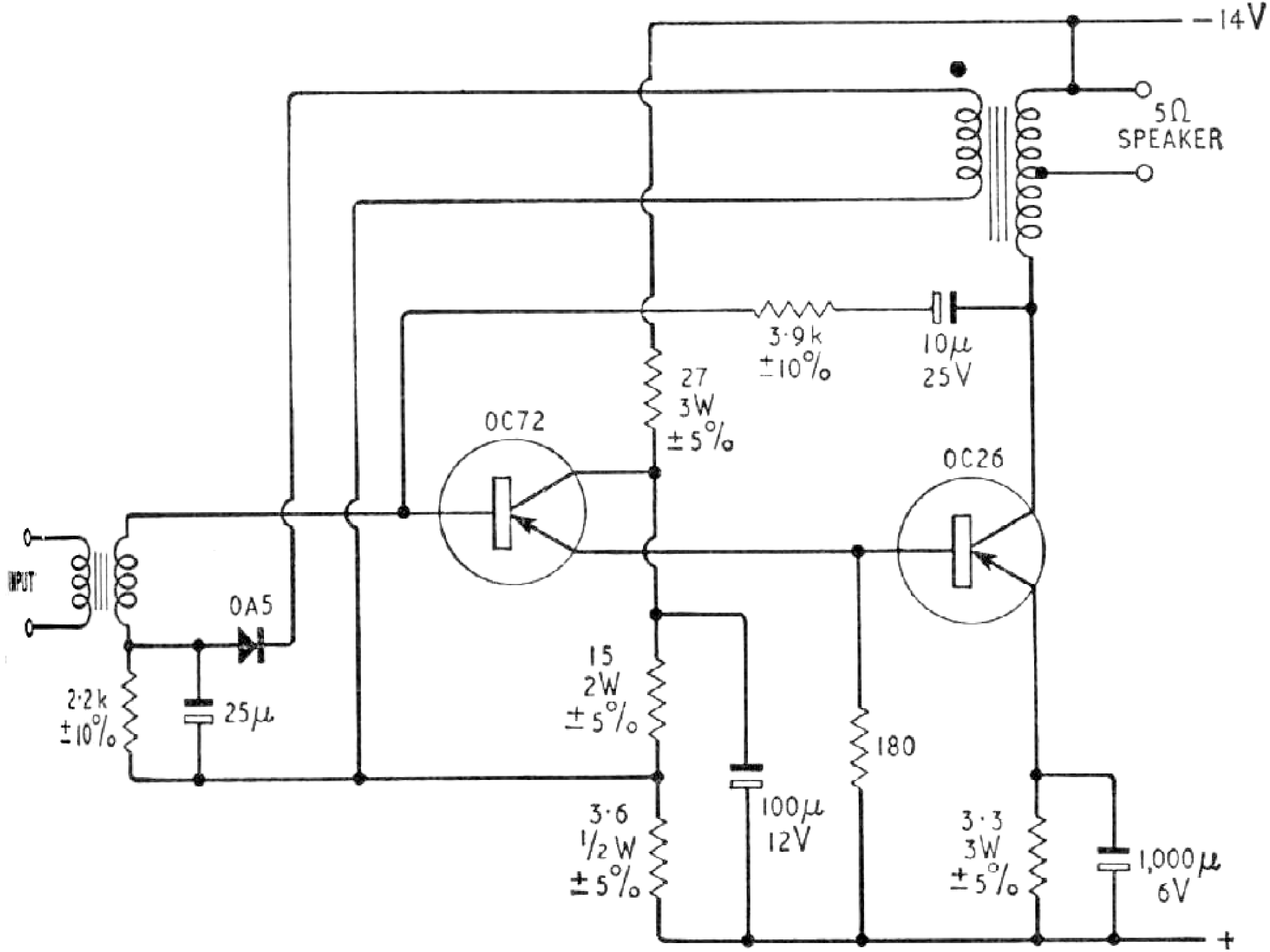
Ⓑ Special high-power transistors.

Fig. 8.11 High-power amplifier.

Circca 1954 30 Watts



Circa 1958
Transformer coupled amp

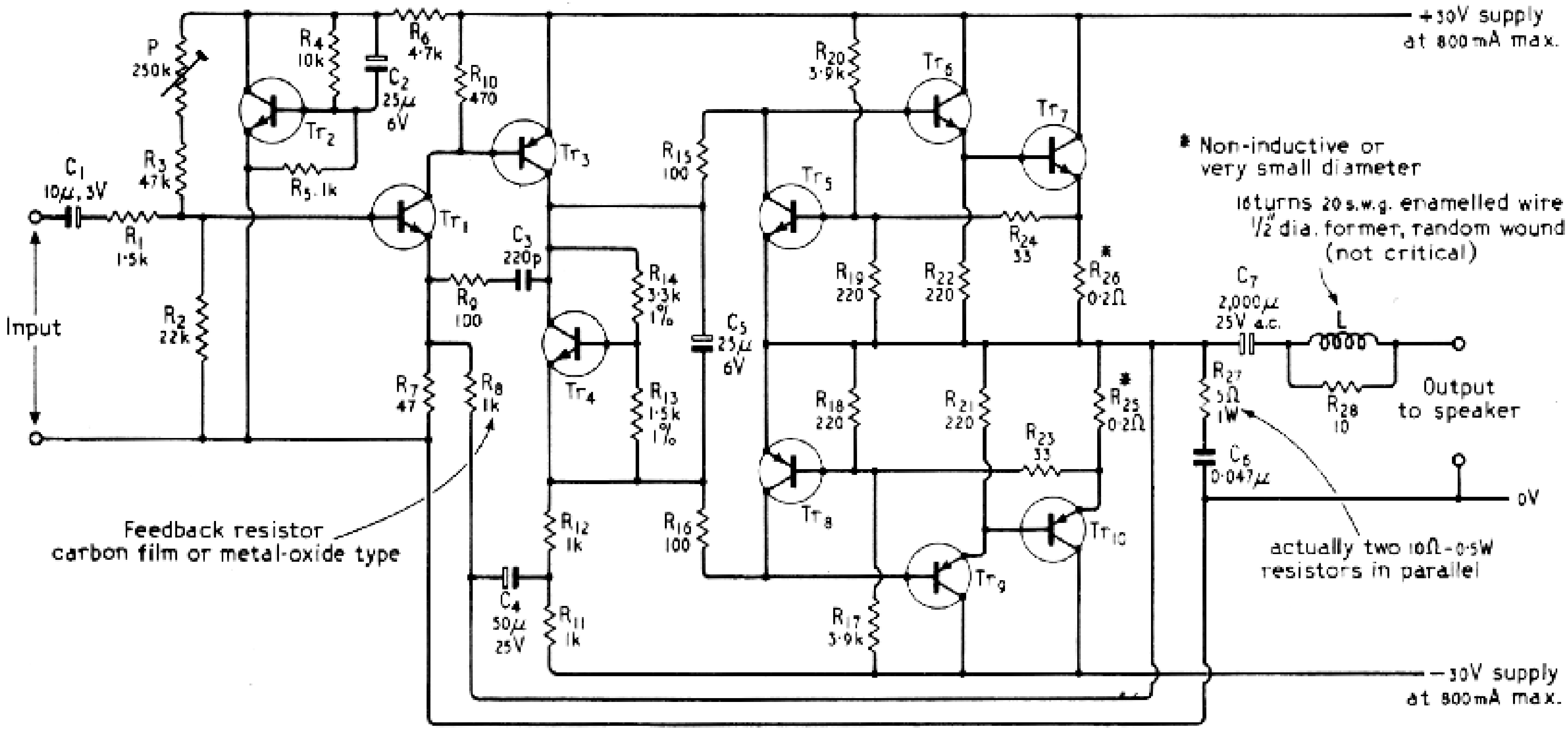


4.5-W *sliding-bias output stage designed by Pawling and Tharma* (*based on* Mullard Technical Communications, *Vol. 4, No. 31*). *The original OC16 has been replaced by OC26.*

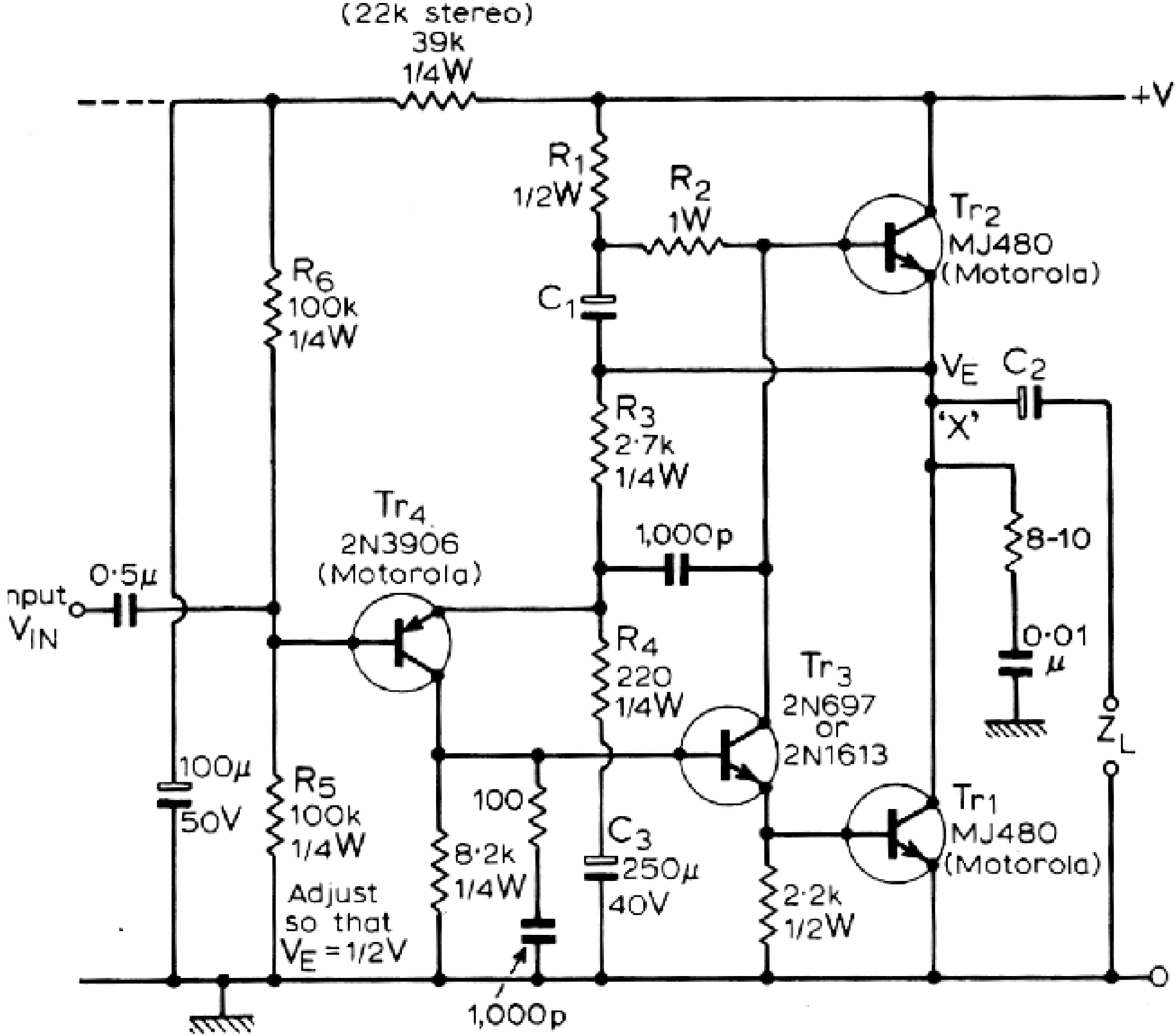
Sliding-bias Amplifier. Wireless World May 1962

“Modern” Solid State Amplifiers

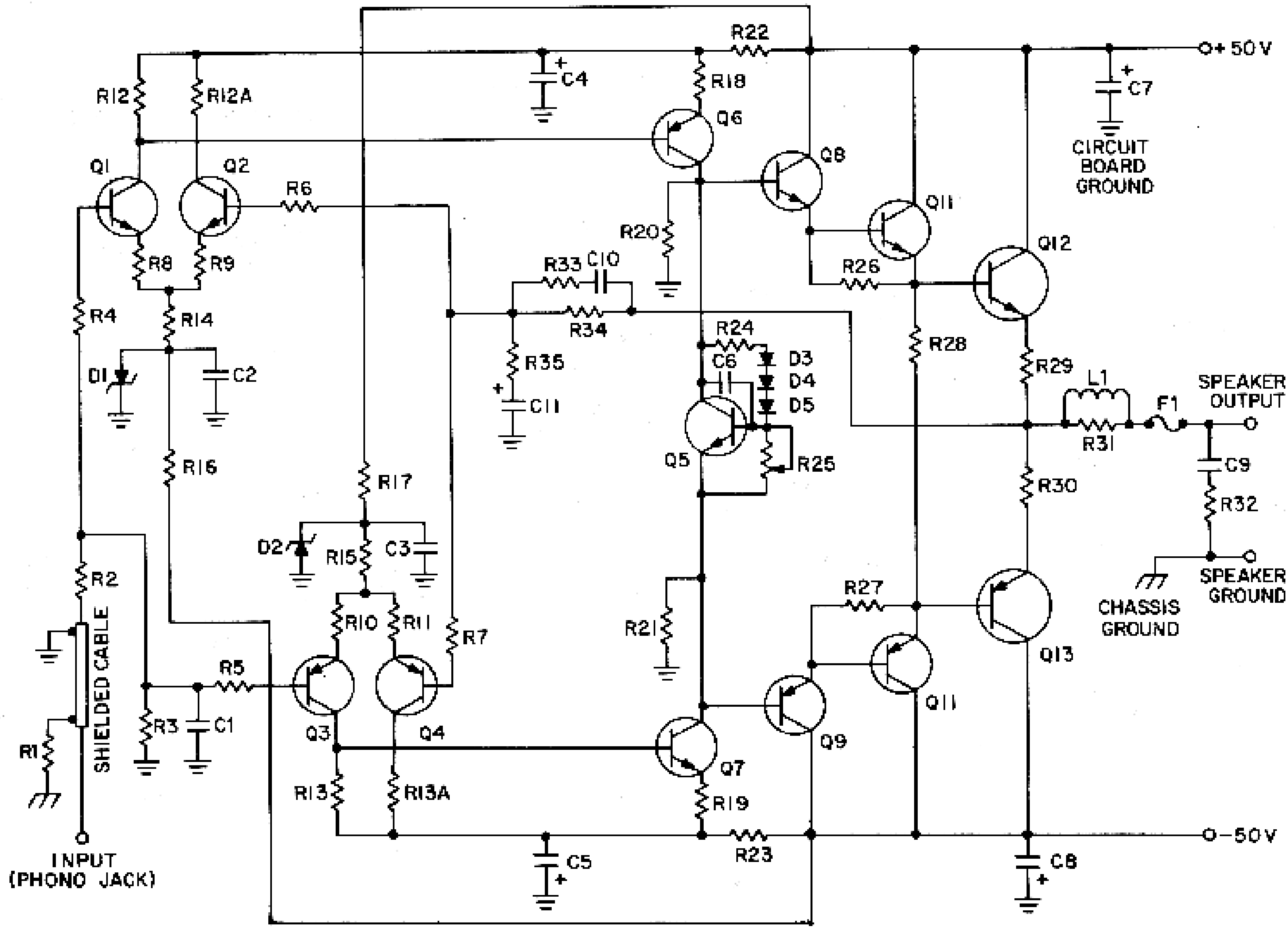
Circuit of complete power amplifier. The transistors used are: Tr_1—40361 (R.C.A.); Tr_2—BC109 (Mullard); Tr_3—40362 (R.C.A).; Tr_4—BC107 (Mullard); Tr_5—BC125 (Fairchild); Tr_6—40361 (R.C.A.); Tr_7—MJ481 (Motorola); Tr_8—BC126 (Fairchild); Tr_9—40362 (R.C.A.); Tr_{10}—MJ491 (Motorola). Note that C_7 is a reversible electrolytic and could be made up of two 4000-μF polarized electrolytics connected 'back-to-back'.



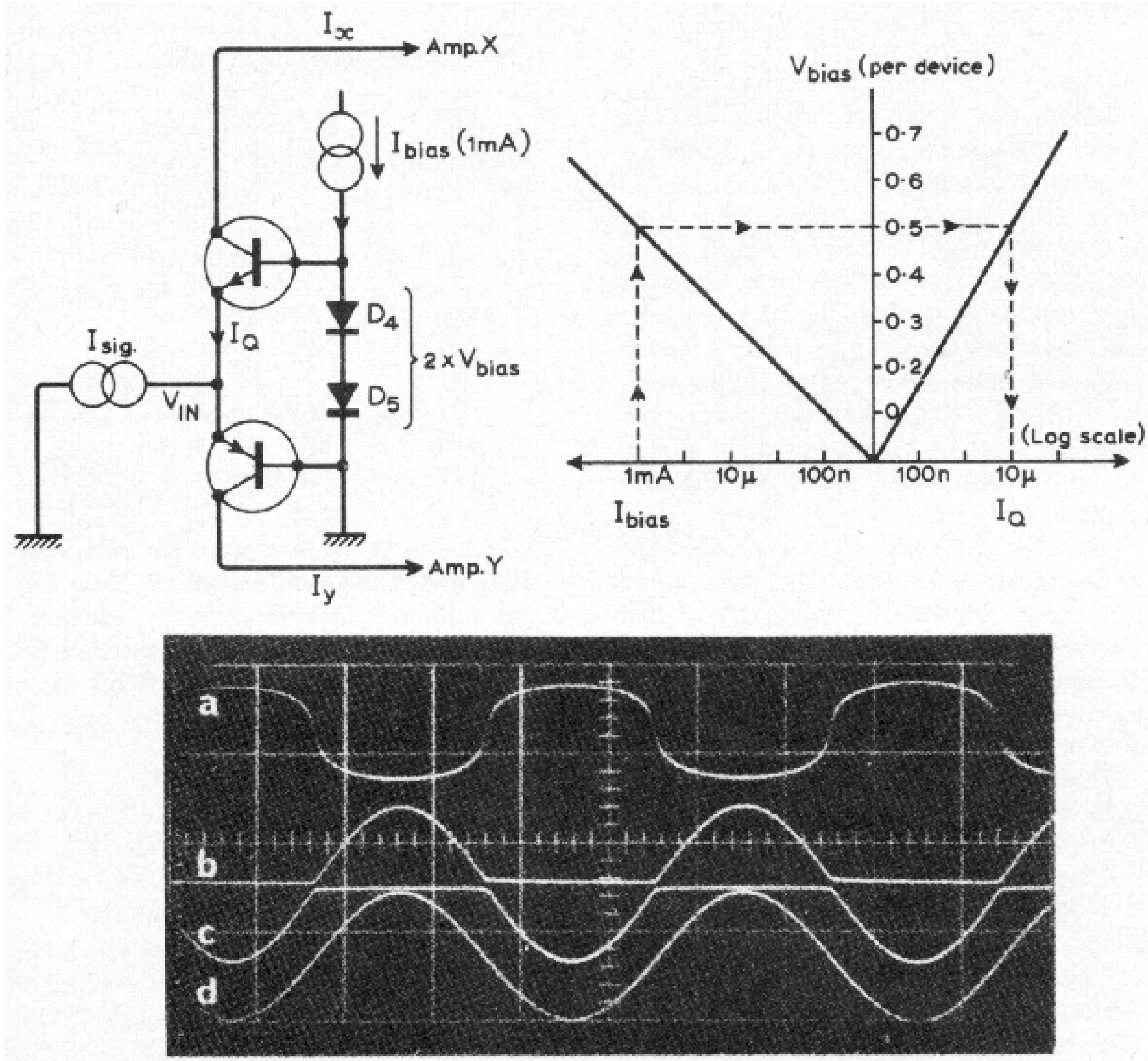
1968 Bailey



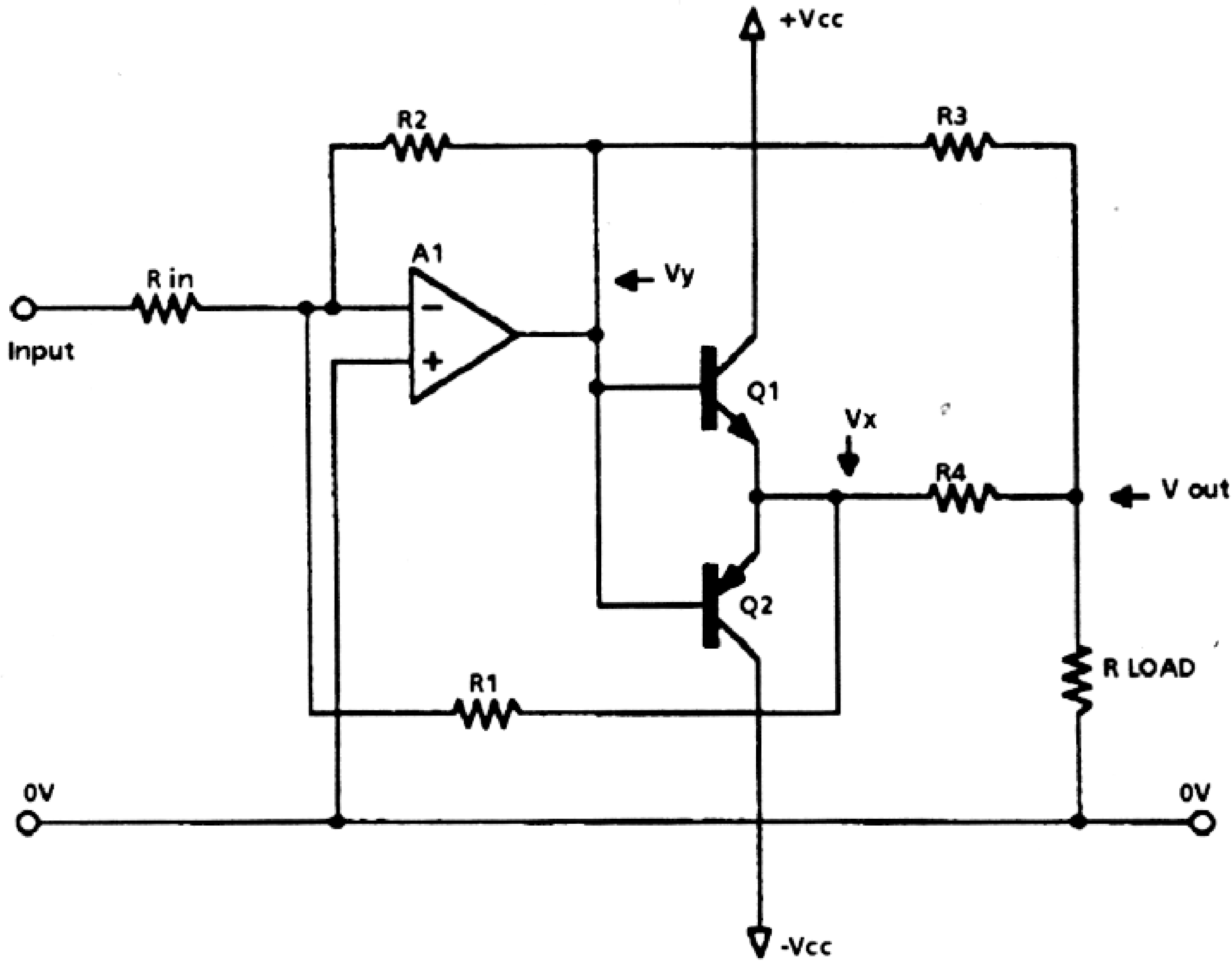
April 1969 Linsley Hood Class A 10 watts



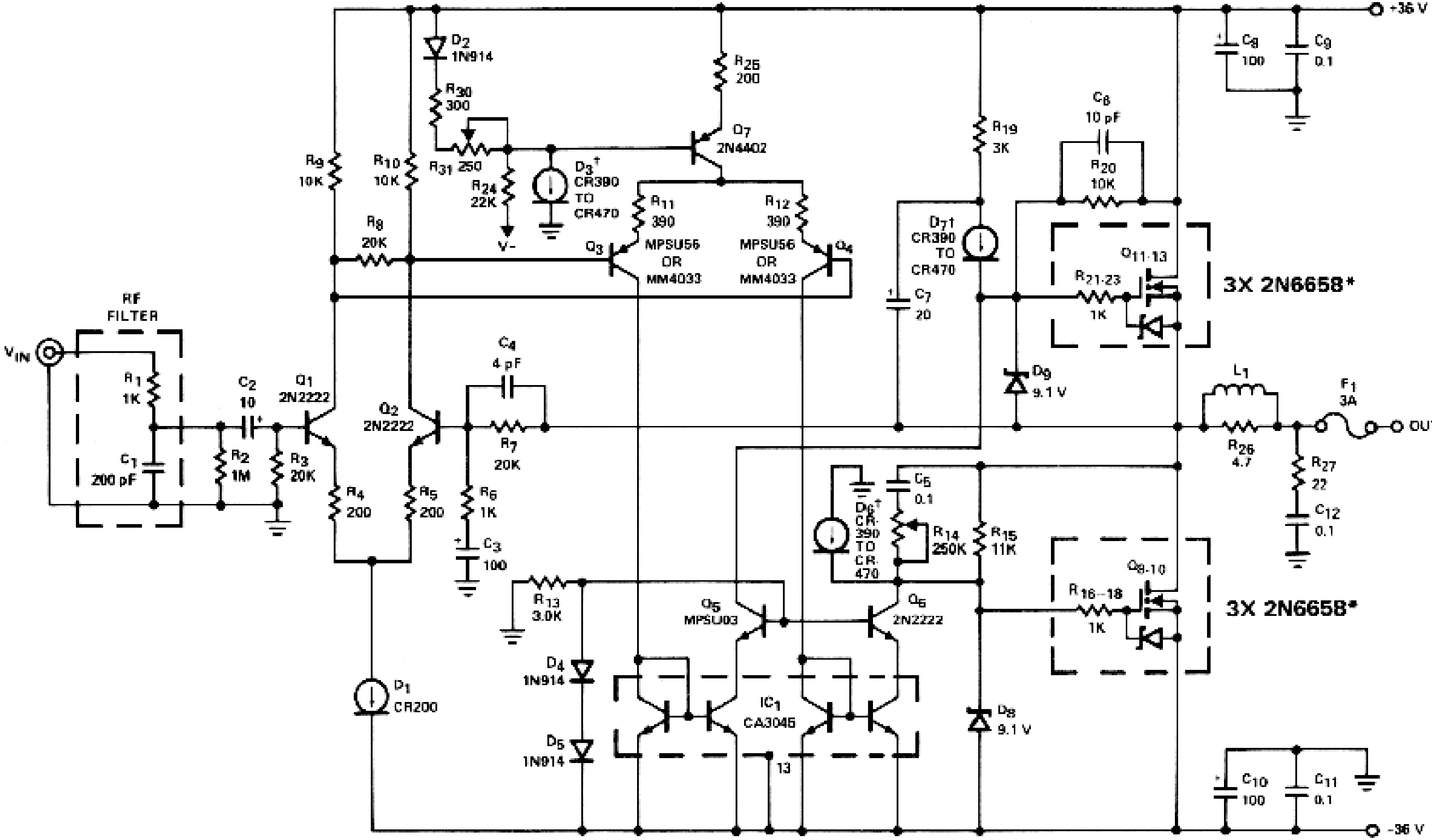
1975 Marshall Leach. Low TIM amplifier



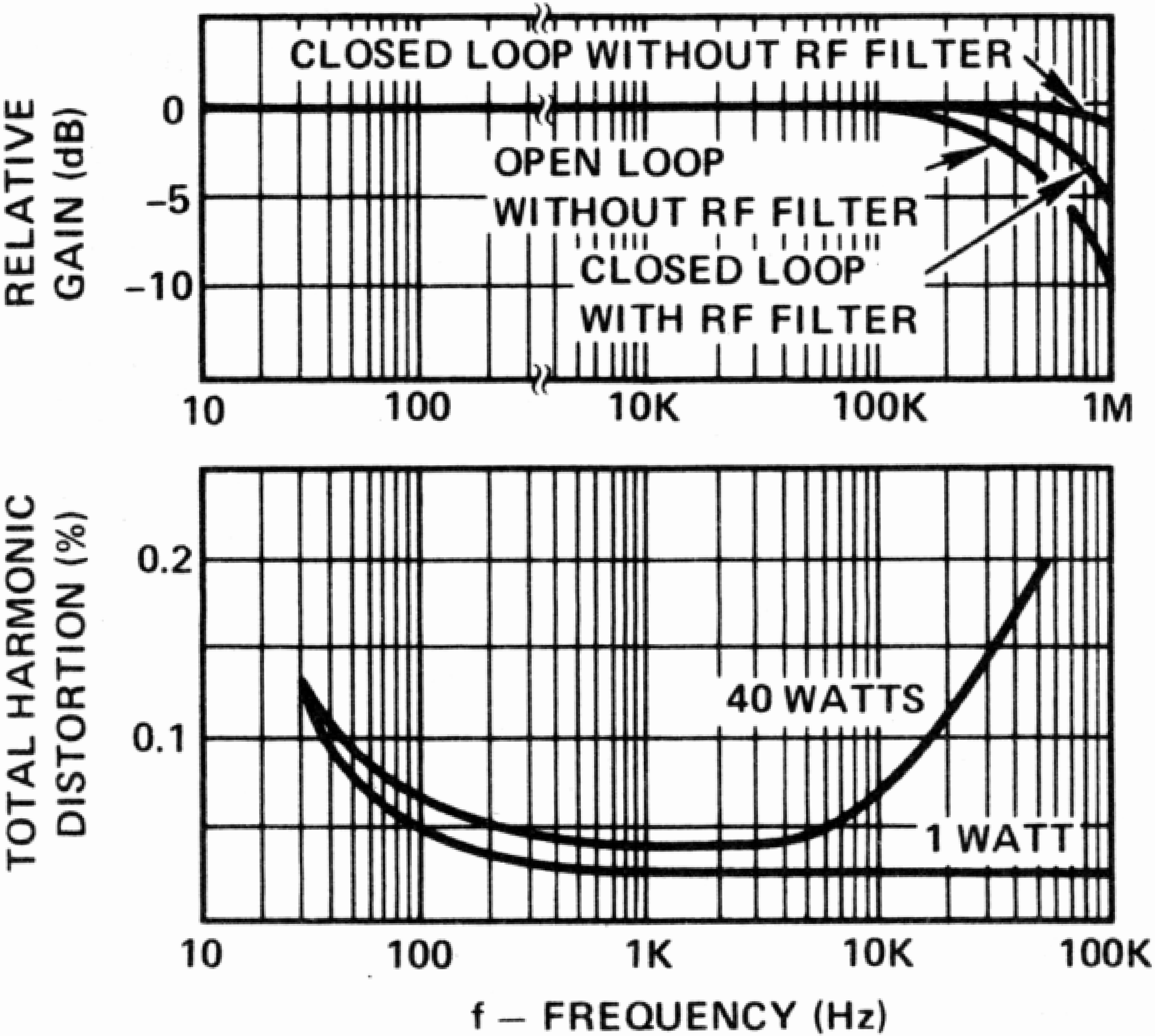
Circa 1973 Blomley. New approach to Class B amplifier design.



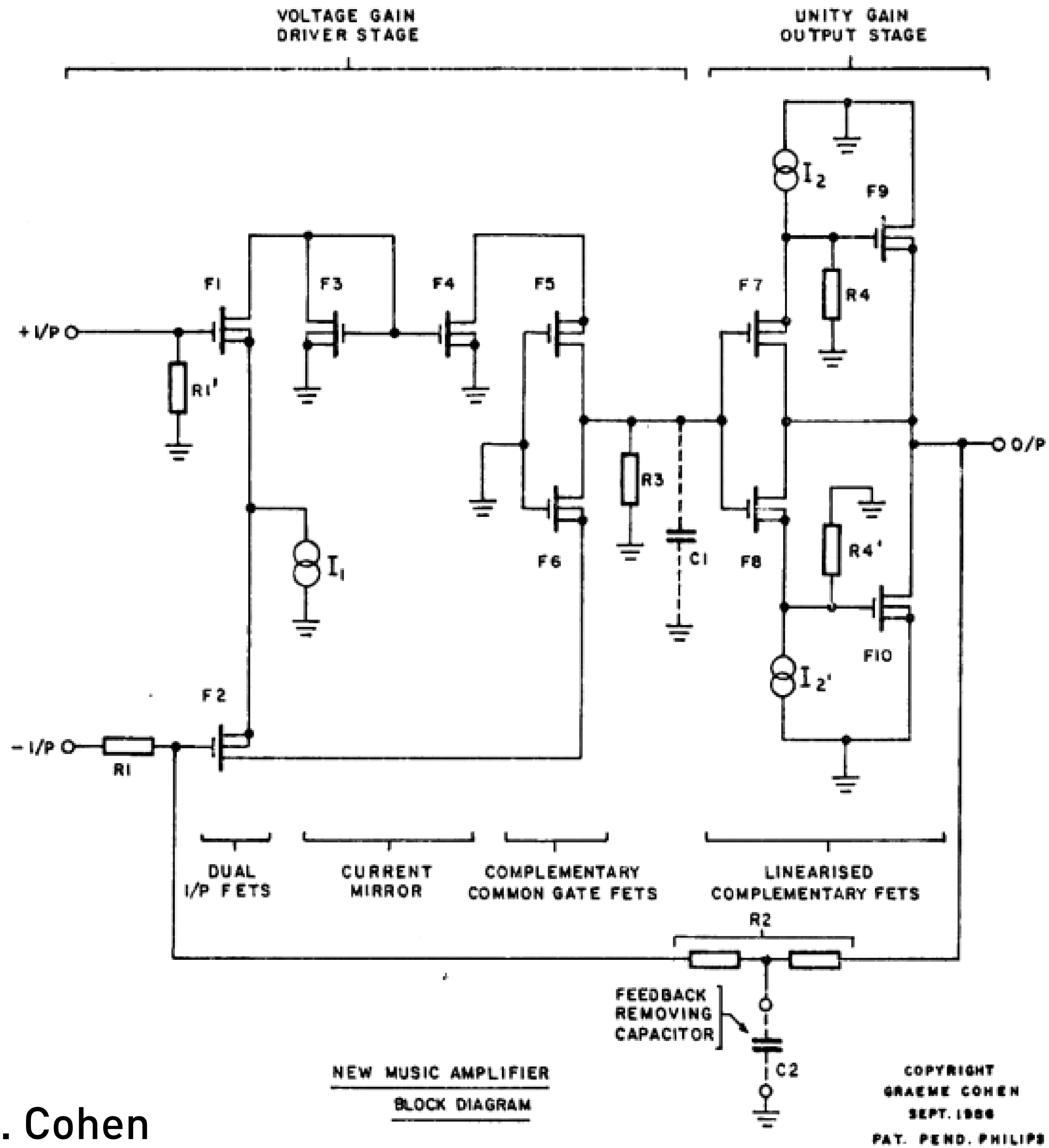
Circa 1975   Quad current dumping amplifier concept.



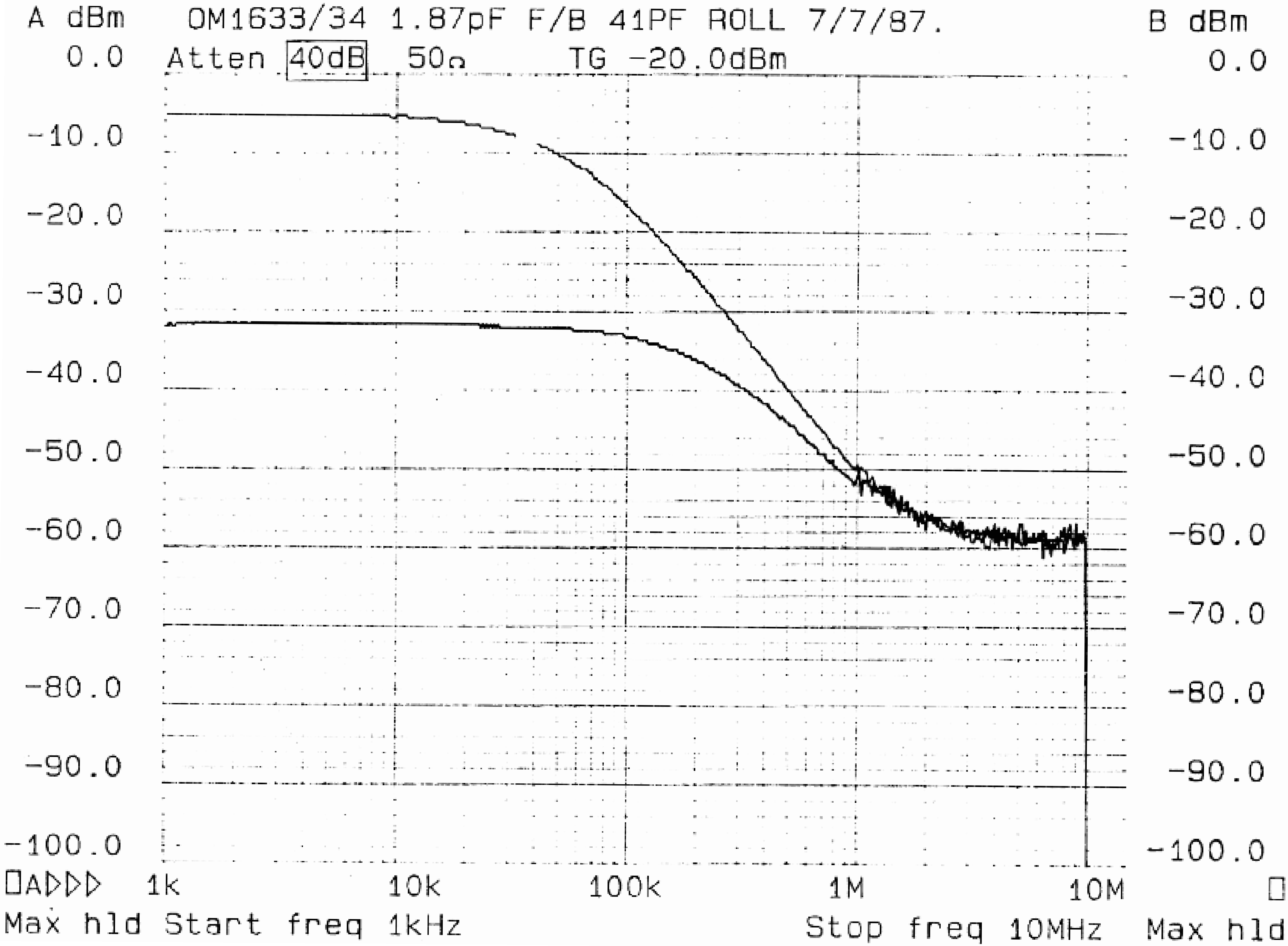
1977 Siliconix VMOS power FET amplifier.

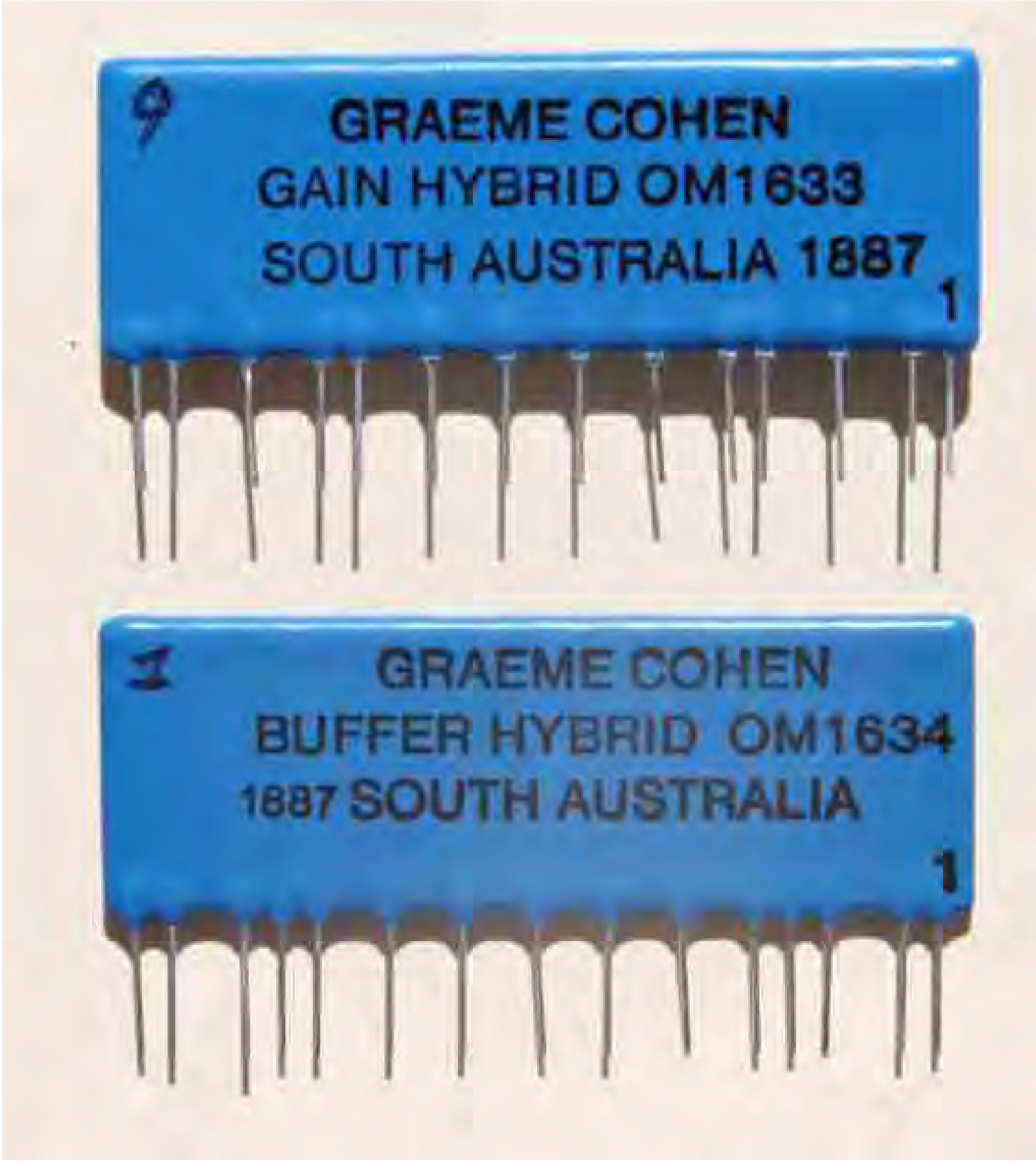


Gain and Distortion vs Frequency



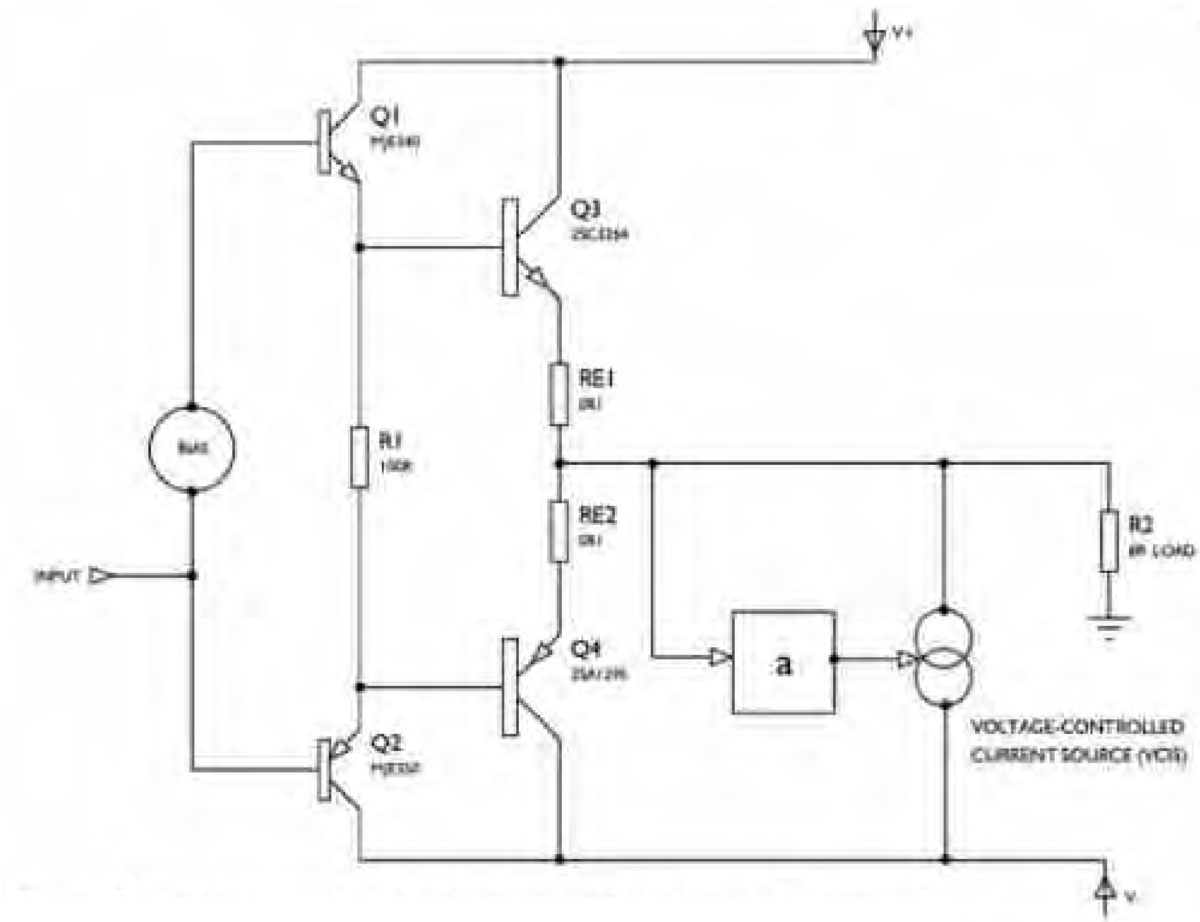
1986 G.J. Cohen


A dBm
0M1633/34 1.87pF F/B 41PF ROLL 7/7/87.
B dBm
0.0
Atten 40dB 50Ω
TG -20.0dBm
0.0
-10.0
-20.0
-30.0
-40.0
-50.0
-60.0
-70.0
-80.0
-90.0
-100.0
1k
10k
100k
1M
10M
Max hld Start freq 1kHz
Stop freq 10MHz
Max hld


GRAEME COHEN
GAIN HYBRID OM1633
SOUTH AUSTRALIA 1887
1
GRAEME COHEN
BUFFER HYBRID OM1634
1887 SOUTH AUSTRALIA
1

Hinged upright for service

1986 G.J. Cohen
Prototype MOSFET amp for Adelaide Festival Centre (FESMOS)



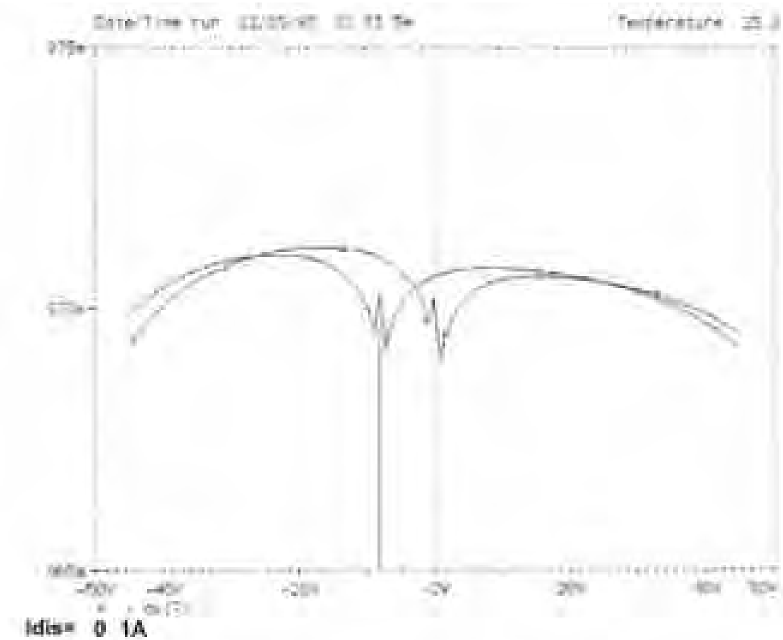
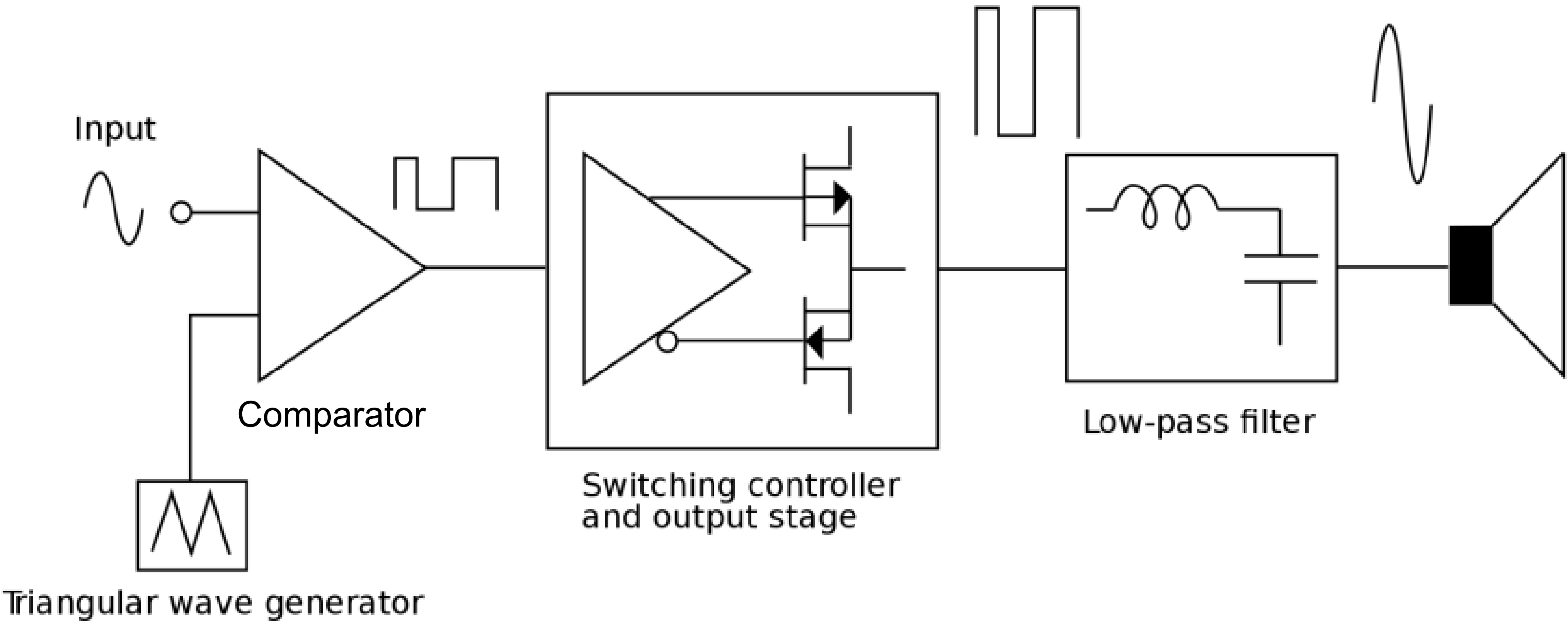


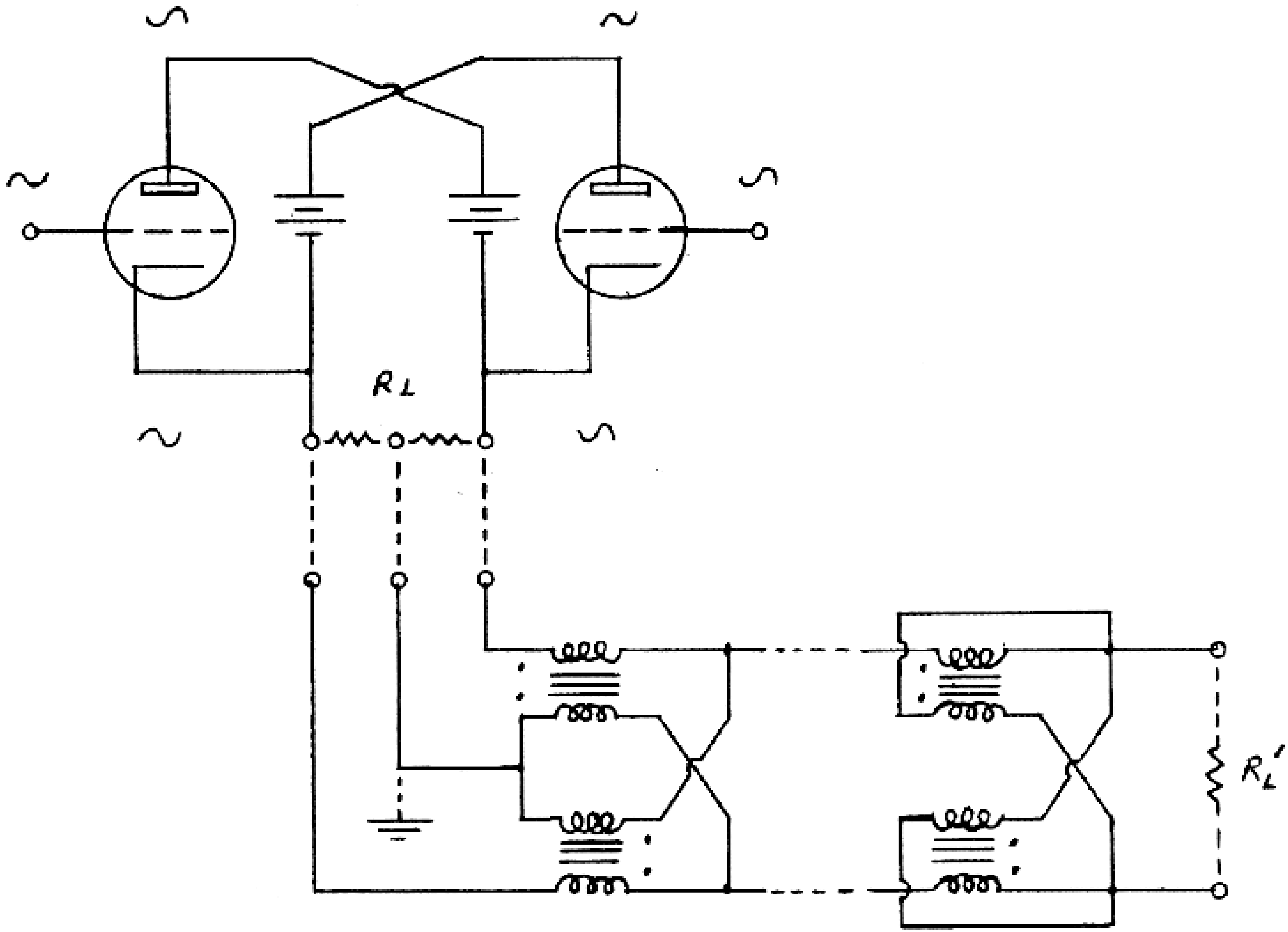
Figure 4: SPICE simulation of the output stage gain variation with and without a constant 1A of displacement current. The central peak is moved left from 0V to -8V

1993 D. Self Current displacement amplifier

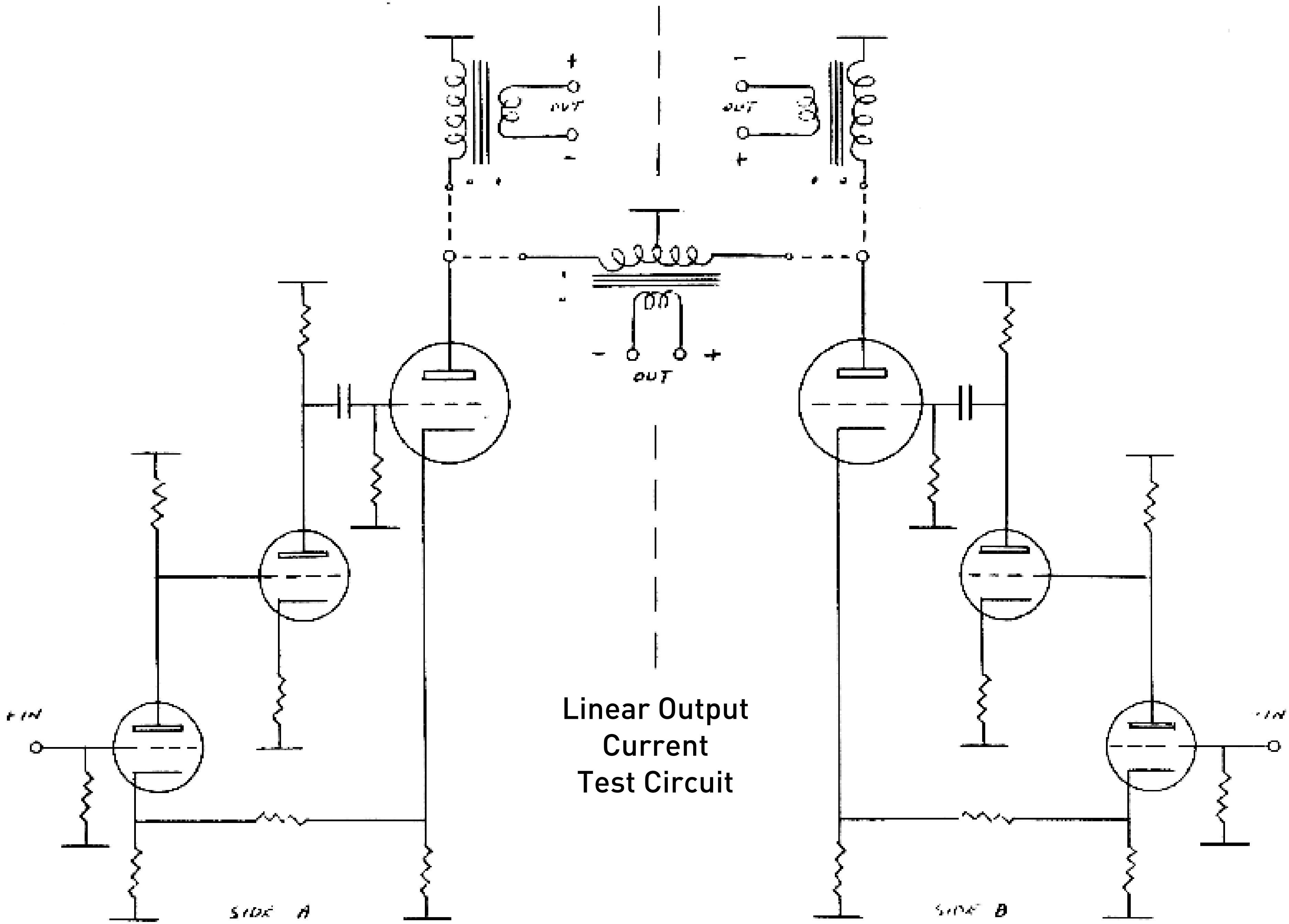
“Other“ Amplifiers



Class D operation



1993 G.J. Cohen
Transmission line transformers. AES Preprint 3692



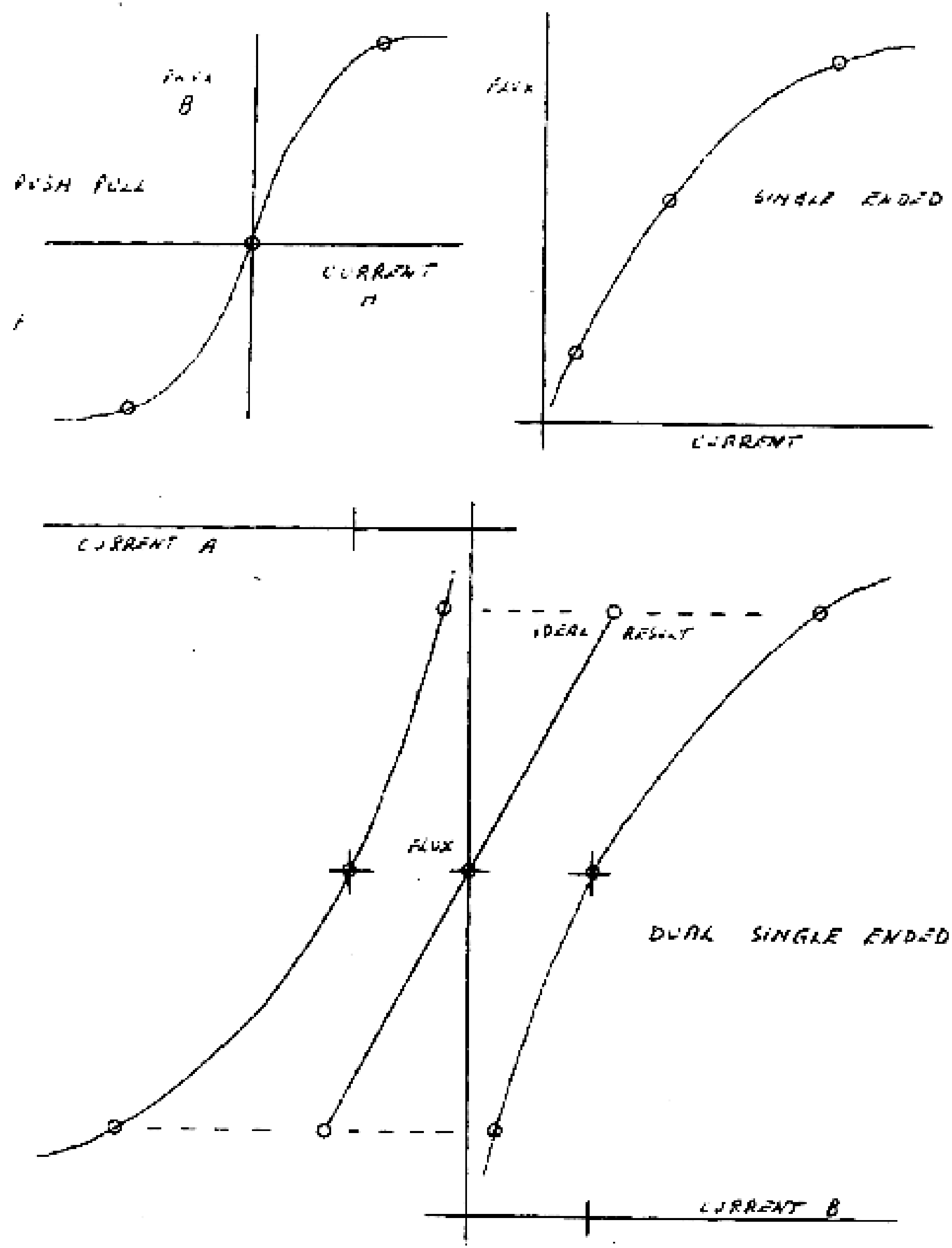
Linear Output
Current
Test Circuit

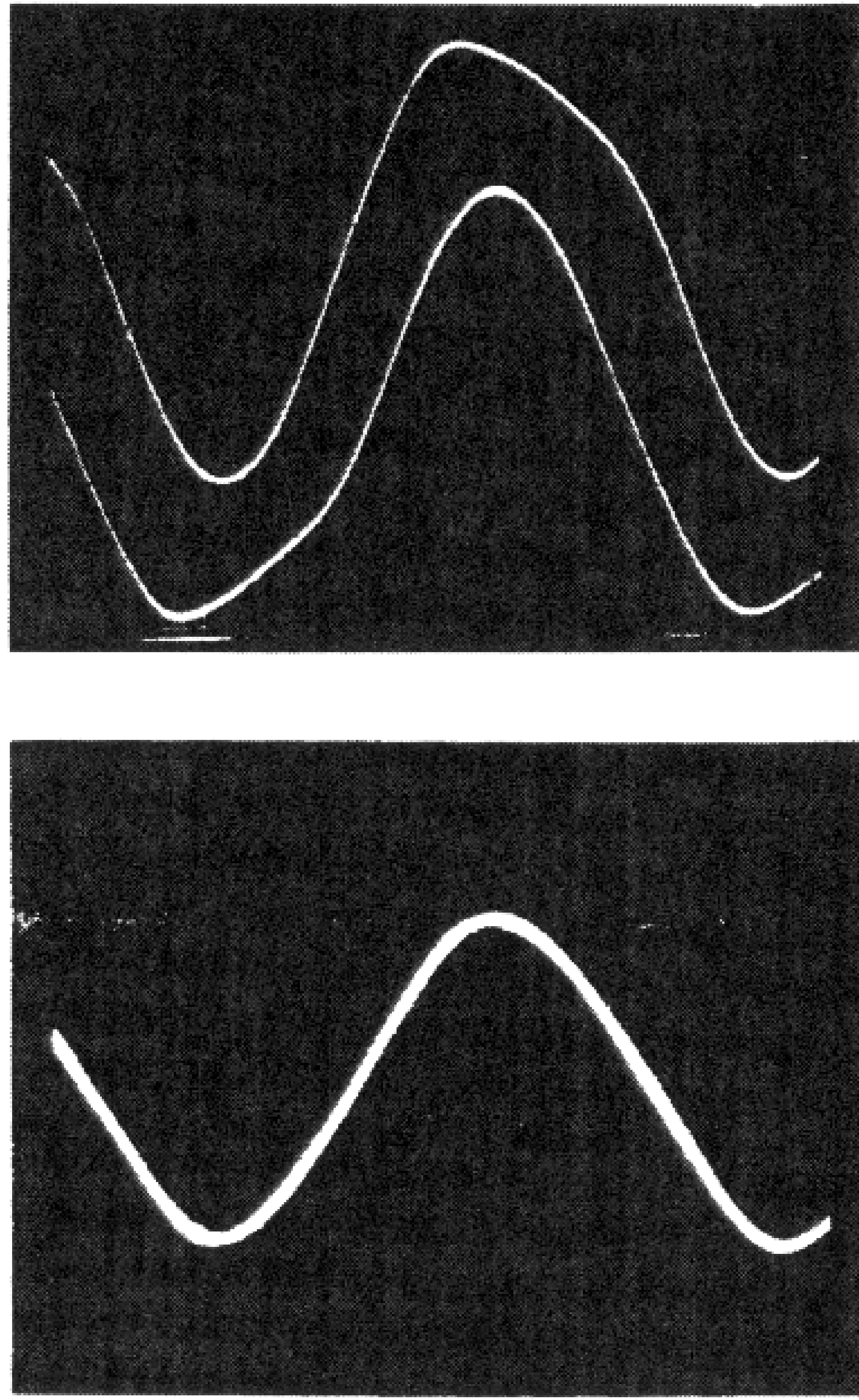
1995 G.J. Cohen
Dual Single Ended Amplifier. AES Preprint 4028

1995 G.J. Cohen

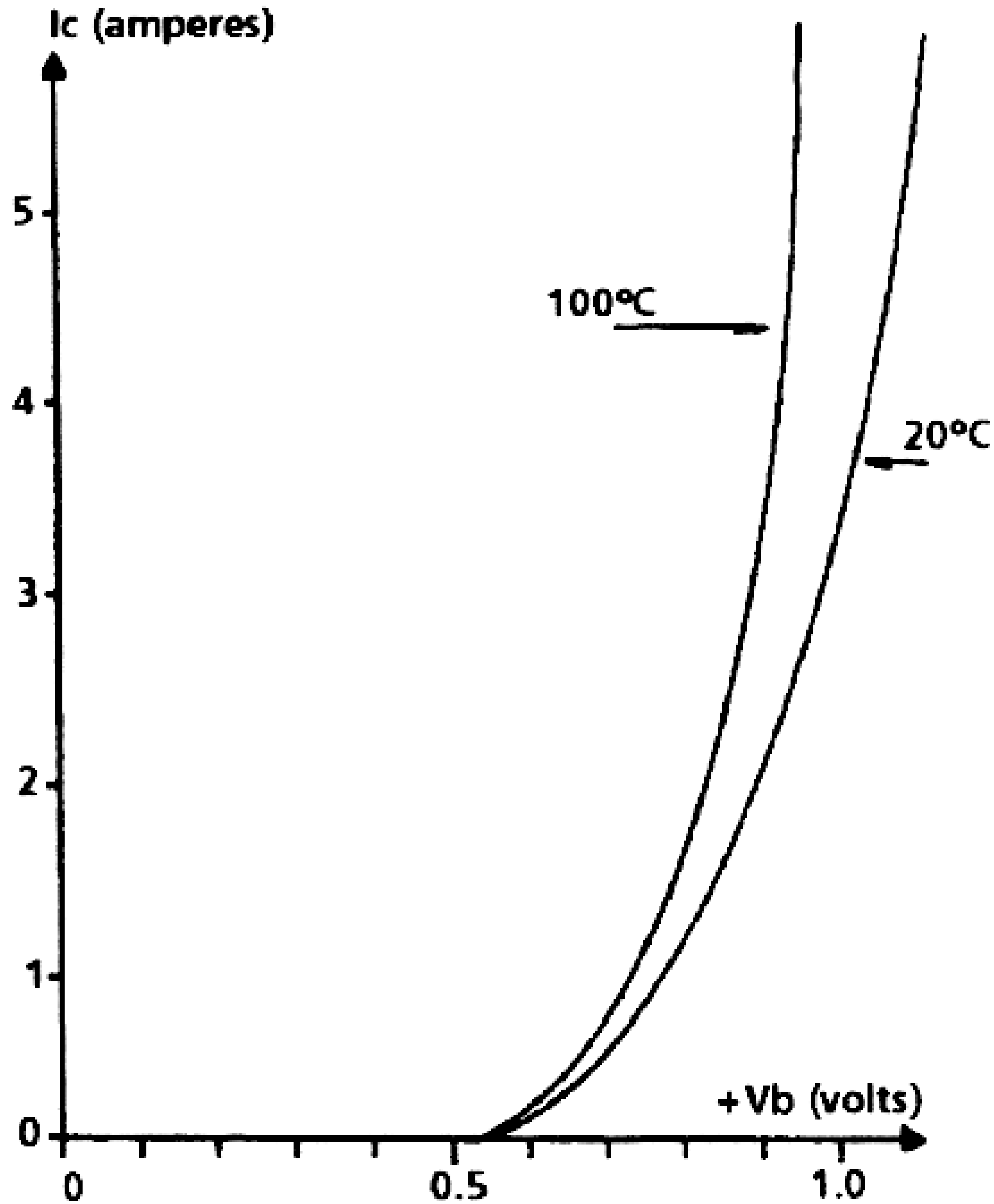
Dual Single Ended Amplifier.

(Showing Distortion Reduction)

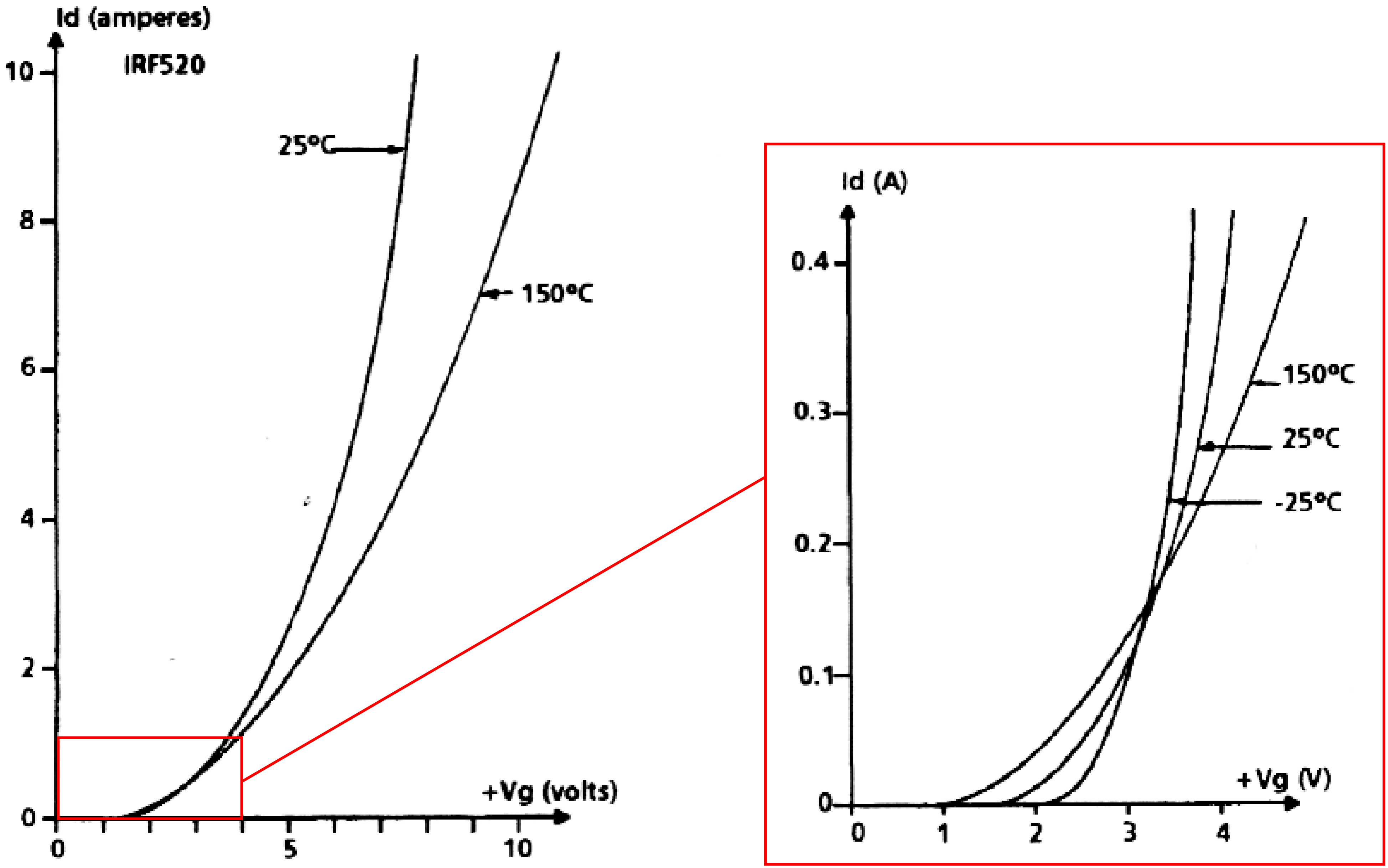




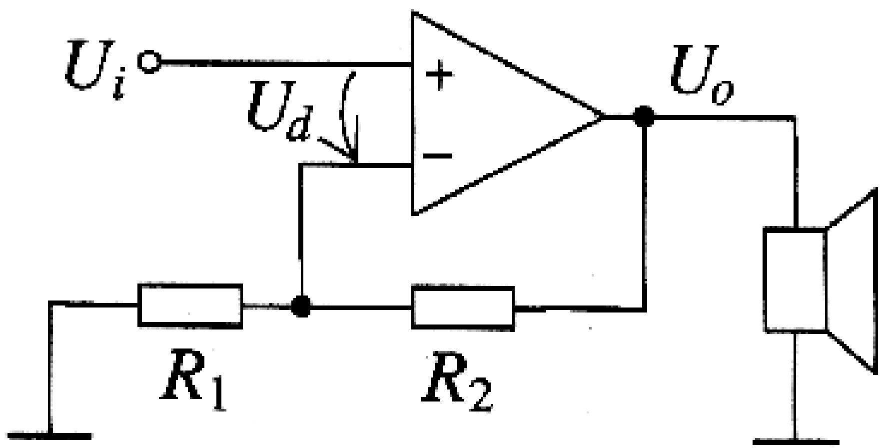
1995 G.J. Cohen
Dual Single Ended Amplifier.
(Showing Distortion Reduction)



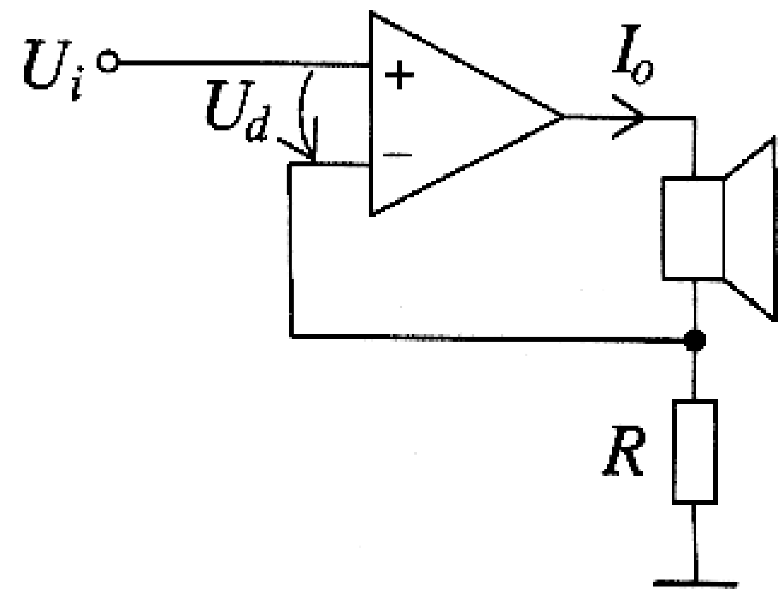
Bipolar Characteristics



MOSFET Characteristics

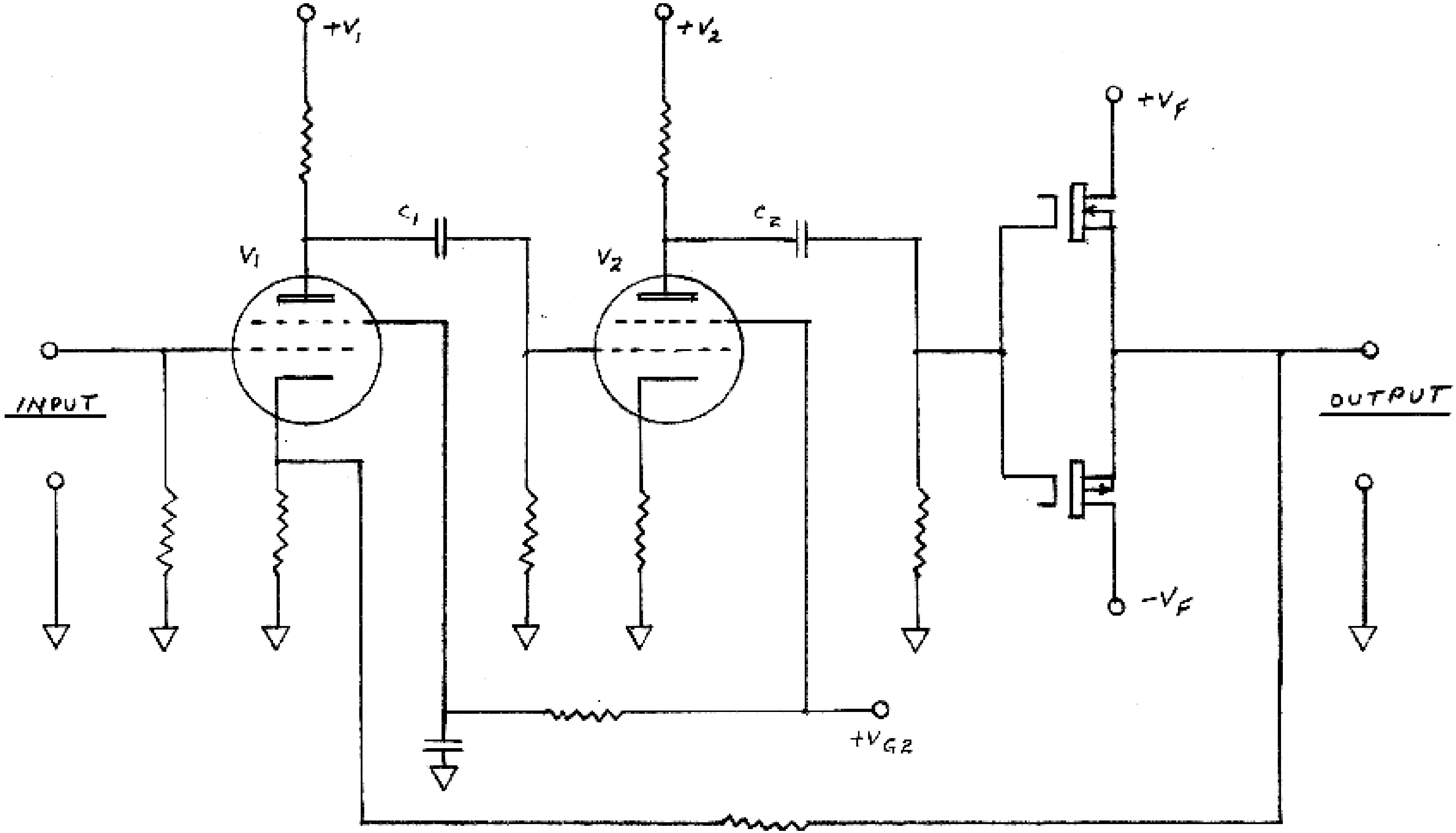


Voltage Output Amplifier



Current Output Amplifier

2010 E. Merilainen
Current Driving of Loudspeakers



2011 G.J. Cohen
Valve - FET Amplifier

1943 Zenith
Hearing Aid Amplifier

2012 G.J. Cohen Headphone Amp

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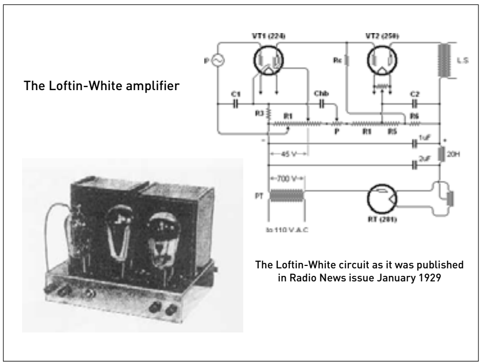
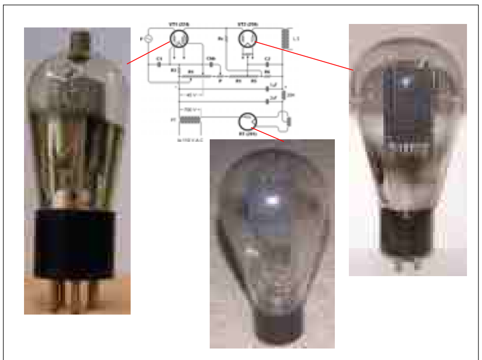
History and design of the audio amplifier

Graeme J Cohen AES Sept 25 2012

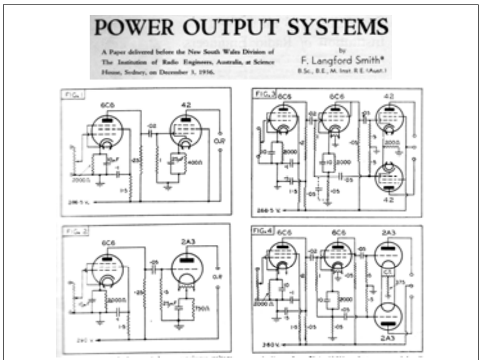
Early High Quality Sound



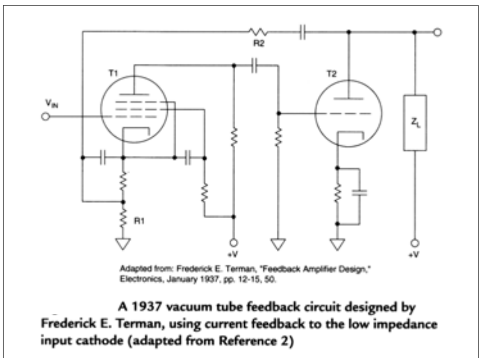
- Possibly earliest famous amp.
- Direct coupled
- Pentode input, Triode output
- Minimum Components



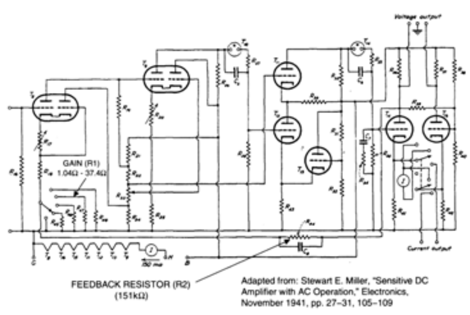
- Pentode silvering from getter
- Triode: solid metal anode
- Half wave rectifier with mesh anode



- F. Langford Smith presentation
- Pentode input stage
- Triode and Pentode outputs
- 1936 designs common in radios

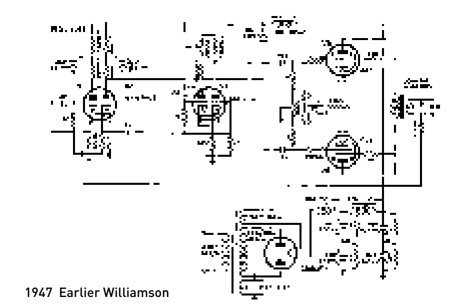


- F.E. Terman design 1937
- Pentode input, Triode output
- Current feedback to I/P cathode
- Forerunner of later designs



A 1941 vacuum tube feedback circuit using current feedback

- Direct coupled push-pull design
- Neon tubes for voltage shift
- Current feedback
- Voltage and current output also used for analog computing

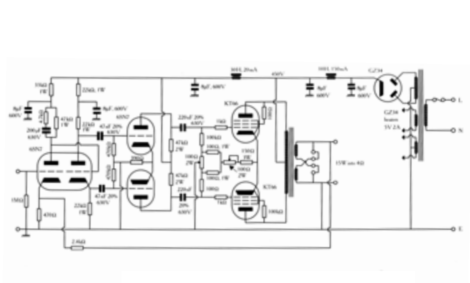


1947 Earlier Williamson

- Early Williamson design 1947
- Triode connected P-P 807's
- DC coupled input stage
- Minimal coupling capacitors

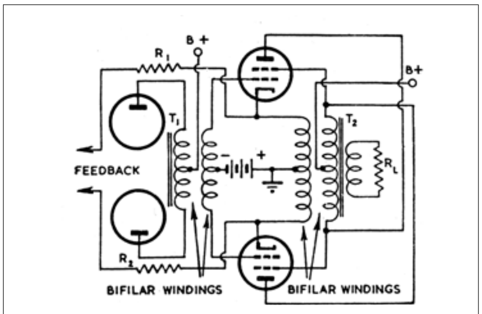
1947 Earlier Williamson. Loop gain and phase.

- Wide response with no feedback
- Well designed output transformer
- Smooth response with feedback
- Controlled phase shift with feedback



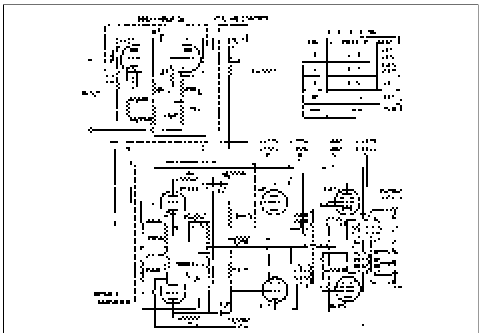
1949 Williamson amplifier

- Later Williamson design 1949
- Triode connected push-pull KT66's
- Extra compensation on input anode
- Extra power supply filter choke



1949 Basic principles of McIntosh Amplifier

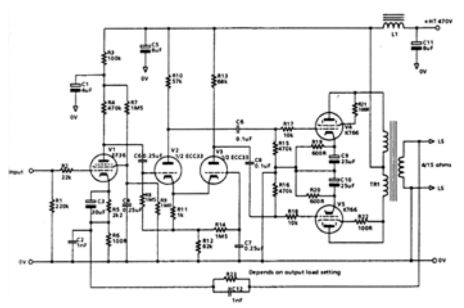
- Bifilar and Trifilar windings
- Screen grids connected to op. anodes
- Cathode windings
- Driver transformer for large swings



1949 Complete 50 watt McIntosh amplifier

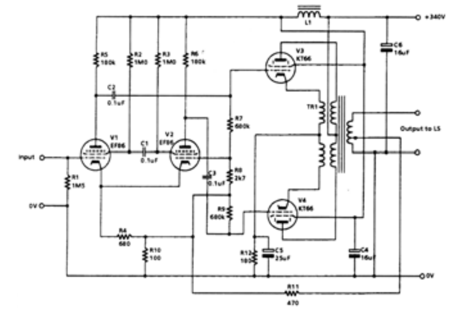
- Also 600 ohms from cathodes
- Fixed bias (maximum output)
- P-P feedback from cathodes
- Preamplifier built in

Quality Sound 1950s



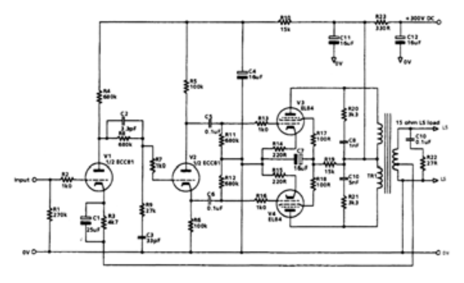
1949 The Leak TL12

- Triode connected KT66's
- ”Long tail” phase splitter
- Single pentode input stage
- Compensation on feedback



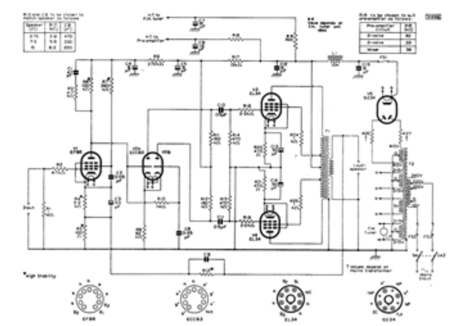
1952 The Quad amplifier

- Pentode connected KT66's
- Cathode windings
- Unique Pentode phase splitter with screen grids coupled



1957 Baxandall's simple amplifier

- Pentode connected EL84's
- Heavy decoupling of output screens
- Feedback from extra tap on O/P T/F
- DC Coupling of I/P with compensation



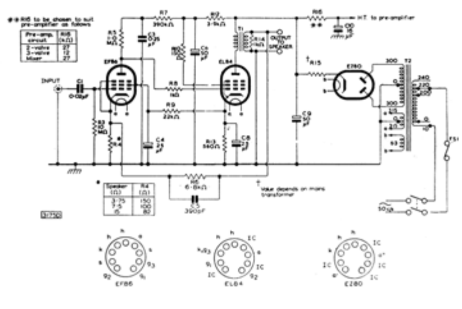
Circa 1959 Mullard 20W amplifier

- ”Ultra Linear” connected O/P stage
- Pentode input stages DC coupled to phase splitter
- Minimal coupling capacitors

Comparison between Triode, Pentode and Distributed-load Operation of EL34s

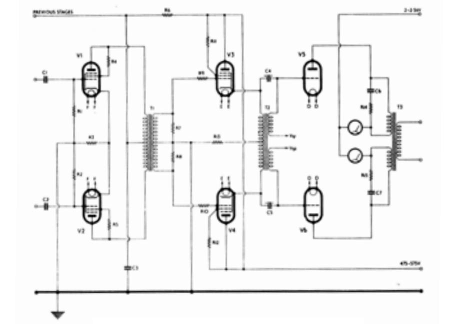
Valve	Mode of Operation	Total Distortion (%) 10W	14W	20W	30W	40W
EL34	Triode connection	0·5	0·7	—	—	—
	Distributed load (a) 20% common winding	0·7	0·8	1·0	1·5	5·0
	(b) 43% common winding	0·6	0·7	0·8	1·0	—
	Pentode connection	1·5	2·0	2·5	4·0	6·0

- ”Ultra Linear” or distributed load
- Triode: low power, low distortion
- Pentode: max power, max distortion
- 20% common. winding:- better
- 43% common. winding:- best



Circa 1959 Mullard 3-3 (3 valves and 3 watts)

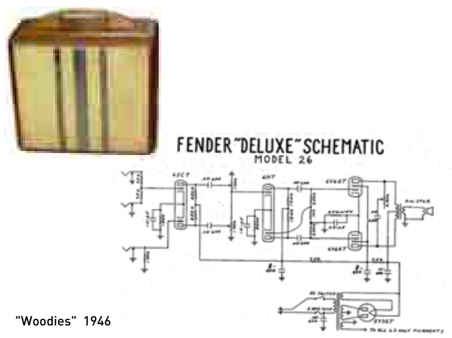
- Input Pentode, starvation condition
- gives maximum gain
- Both stages DC coupled
- Class “A” operation, 3 watt output



Circa 1959 General Electric Class AB2 600-1100 watt amplifier.

- Class “AB2" operation
- All stages triode connected
- Driver T/F because of grid current
- Equal turns on driver pri & sec with coupling caps. from cathodes to grids

Guitar Amplifiers

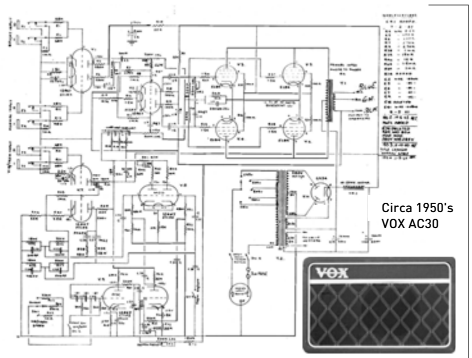


"Woodies" 1946

- Fender, “first” amplifier for guitars
- ”Woodies” due to polished cabinets
- Input mixing stage, simple splitter
- No Feedback gives soft overload

Circa 1950's

- Marshall, later & high power
- More complex
- Vibrato/tremelo added

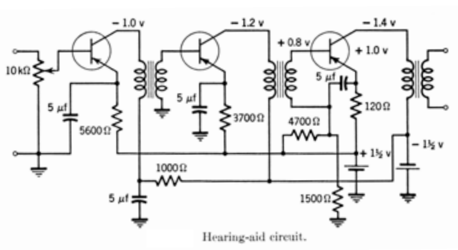


Circa 1950's
VOX AC30

- Vox, later design
- Also complex additions
- Some small sized models

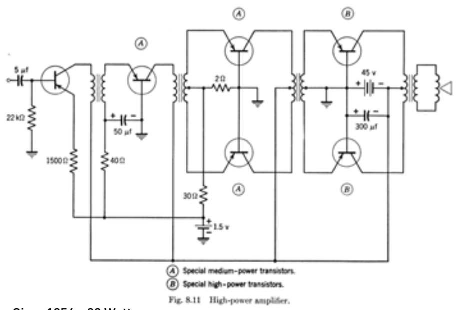
Early Solid State Amplifiers

- Brattain, Bardeen & Schockly invented the transistor in December 1947 at Bell Labs.



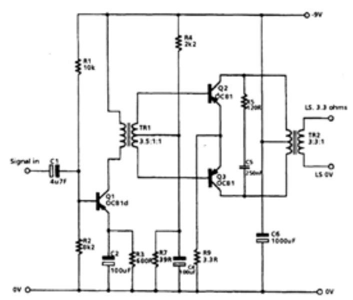
Circa 1953

- Germanium PNP Transistor 1953
- Interstage coupling transformers
- Four only capacitors of same value
- Two of 1.5 volt batteries (+/- supply!)



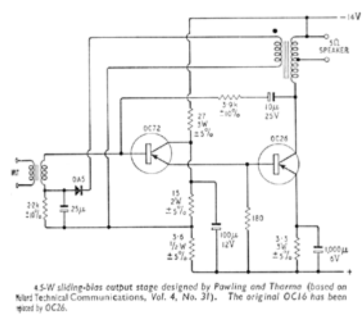
Circa 1954 30 Watts

- High power (30W) Germanium power
- Grounded base stages, except input
- due to poor response of devices
- Therefore coupling transformers



Circa 1958
Transformer coupled amp

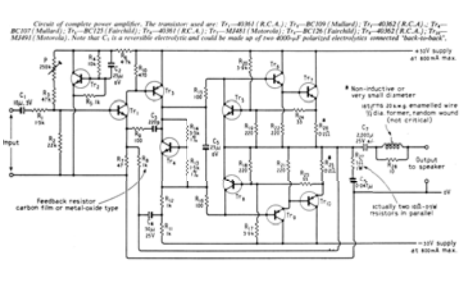
- Germanium with better freq. response
- Common emitter stages
- Still transformer coupled
- High gain, no feedback
- Commonly used in “Tranny” Radios



Sliding-bias Amplifier. Wireless World May 1962

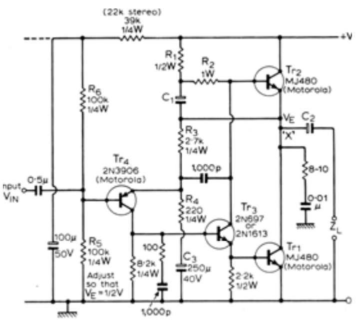
- Class “A” low to high bias O/P stage
- Bias increased for higher average signal. i.e. Low average dissipation
- Possibly for radio comms use

“Modern” Solid State Amplifiers



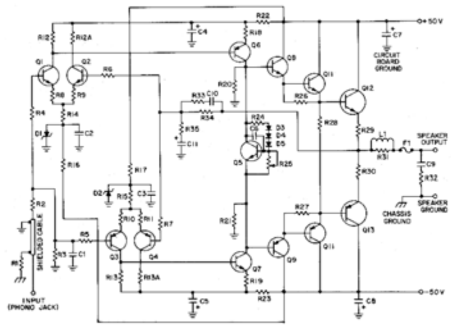
1968 Bailey

- Early use of symmetrical voltage rails
- Early use of overload protection
- Early bias compensation on input
- Symmetrical output stage and Zobel network



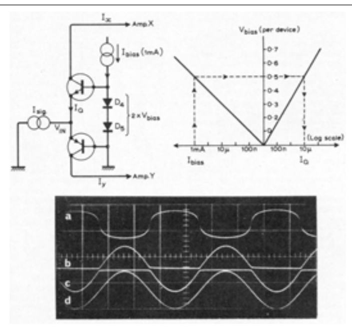
April 1969 Linsley Hood Class A 10 watts

- J.L. Hood 10 watt Class “A”
- NPN output transistors only
- Very high frequency driver transistors so loop gain less than unity at 180°
- No crossover distortion



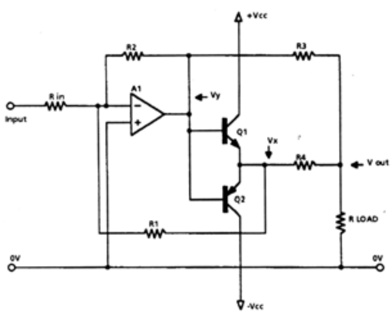
1975 Marshall Leach. Low TIM amplifier

- Low transient intermod. distortion
- Fully complementary-symmetry
- D.C. coupled
- 20dB or less feedback
- RFI input protection



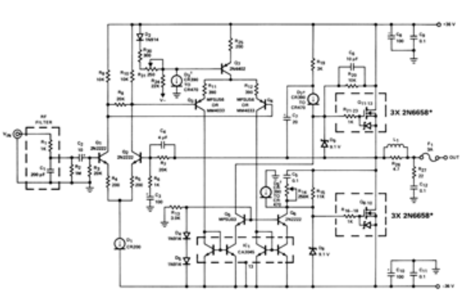
Circa 1973 Blomley. New approach to Class B amplifier design.

- Single ended input current switched to P-P output current in class “B”
- Bipolar transistor true LOG operation
- Thermal tracking of this function



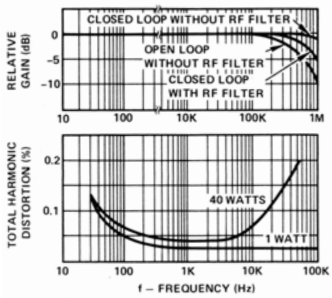
Circa 1975 Quad current dumping amplifier concept.

- QUAD unique current dumping amp.
- Class “A” at low level & Class “B” at high levels via feedback paths
- The four feedback components are a frequency dependant balanced bridge



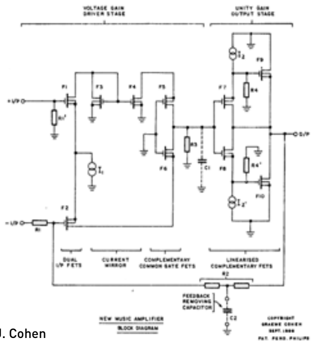
1977 Siliconix VMOS power FET amplifier.

- Quasi-complimentary N-Channel VMOS only available at this time
- Hence current mirrors used for drive
- Low feedback approximately 20dB

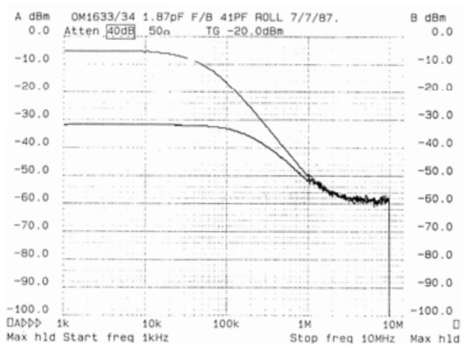


Gain and Distortion vs Frequency

- Low distortion from 40Hz - 20kHz
- Open loop -3dB to 40kHz
- RFI input filter curve shown

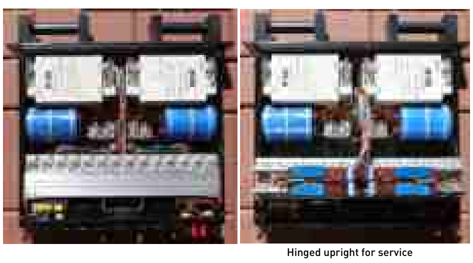

1986 G.J. Cohen

- All FET design, used hybrid
- Single pole response (C1), gate cap.
- Modest feedback
- Balanced input



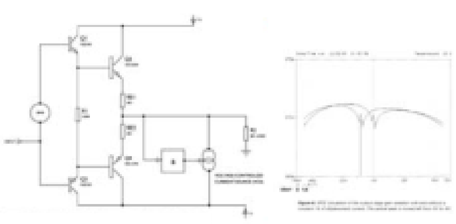
- Open loop -3dB to 40kHz
- Closed loop -3dB to ~150kHz
- Overall smooth response
- Response to DC. No coupling, feedback or bypass capacitors used

- Hybrids with minimal ext. components
- Used in FESMOS amplifiers
- Ease of servicing (replace hybrids)



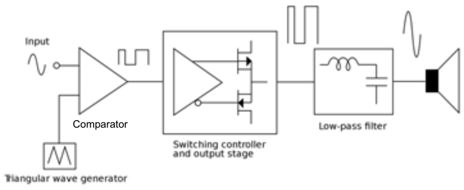
1986 G.J. Cohen
Prototype MOSFET amp for Adelaide Festival Centre (FESMOS)

- Prototype for FESMOS development
- 500 watts per channel
- Heatsink folds up for servicing
- 2RU for proto., Conv. cooling


1993 D. Self Current displacement amplifier

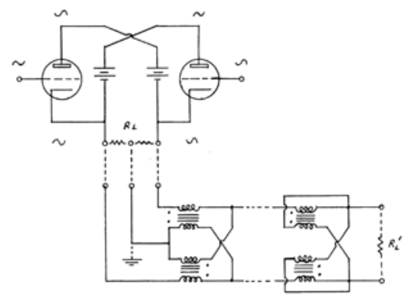
- Bias current change with signal
- Similar but opposite to sliding-bias
- Question output current (bias) change under dynamic conditions

“Other“ Amplifiers



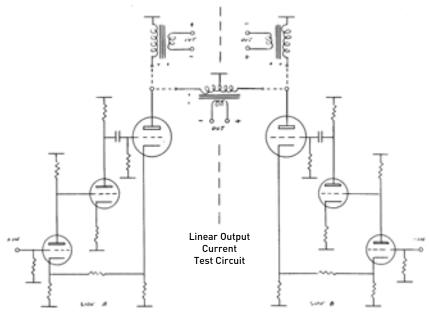
Class D operation

- Class “D” efficient operation
- Uses pulse width modulation
- Low pass filter before speaker
- Possible radiation of switching noise



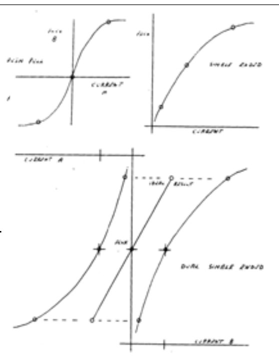
1993 G.J. Cohen
Transmission line transformers. AES Preprint 3692

- Bifilar auto-transformer (No DC)
- Triode anode and cathode output
- Lower turns, tighter coupling
- Two floating power supplies



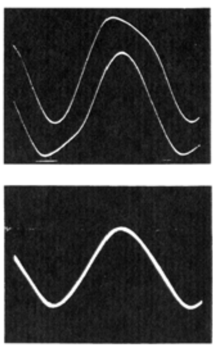
1995 G.J. Cohen
Dual Single Ended Amplifier. AES Preprint 4028

- 2 single ended Class “A” per channel
- Test circuit to generate current O/P to compare P-P, and 2 Class “A”, added



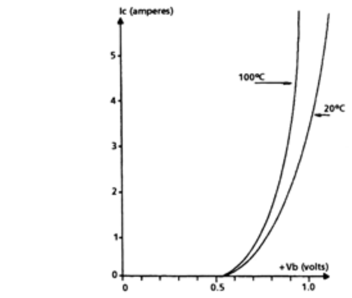
1995 G.J. Cohen
Dual Single Ended Amplifier.
(Showing Distortion Reduction)

- Two single ended transformers showing some distortion reduction



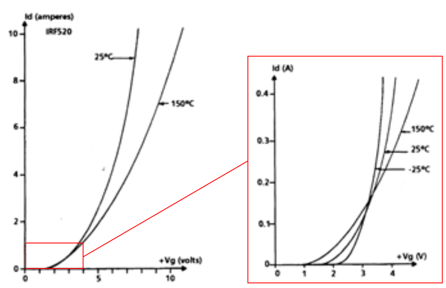
1995 G.J. Cohen
Dual Single Ended Amplifier.
(Showing Distortion Reduction)

- Individual waveforms approaching overload
- Combined waveforms



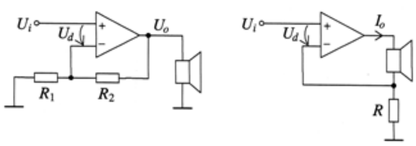
Bipolar Characteristics

- Bipolar junction transistor curves
- Steep gradient due to high gain
- Has sharp turn-on for voltage drive
- Possible thermal run-away



MOSFET Characteristics

- Field Effect Transistor curves
- Gentle gradient, lower gain
- Gradual turn-on
- Reduced current with higher temp.
- Zero temperature coefficient at “A” to “AB” transition

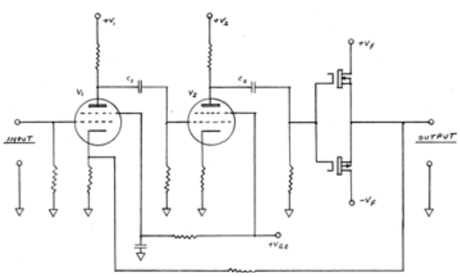


Voltage Output Amplifier

Current Output Amplifier

2010 E. Merilainen
Current Driving of Loudspeakers

- Current drive to speakers
- Plus: holds current at resonance
- Minus: has low damping for transients
- Speakers are usually designed for voltage (low impedance) drive



2011 G.J. Cohen
Valve - FET Amplifier

- Valve input & driver with FET output
- Valves for voltage gain
- FETs for current gain
- Valve amp with no O/P transformer
- 2 coupling caps. Min. phase shift
- No bypass caps. in feedback path

1943 Zenith
Hearing Aid Amplifier

- 1943 Hearing aid amplifier
- Valves developed for this in 1942
- Inbuilt mic. above clip for coat pocket
- Separate batteries and earpiece

2012 G.J. Cohen Headphone Amp

- Output impedance setable from one ohm up to 120 ohms (DIN Spec)
- Valves are low distortion types