US007053714B1

(12) **United States Patent**
Fields et al.

(10) **Patent No.: US 7,053,714 B1**
(45) **Date of Patent: May 30, 2006**

(54) **METHODS AND APPARATUS FOR SWITCHING BETWEEN CLASS A AND A/B OPERATION IN A POWER AMPLIFIER**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **11/248,533**

(22) Filed: **Oct. 12, 2005**

(51) **Int. Cl.**
H03F 3/26 (2006.01)

(52) **U.S. Cl.** **330/276**; 330/165

(58) **Field of Classification Search** ..... 330/276, 330/165, 251, 207 A, 311
See application file for complete search history.

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(57) **ABSTRACT**

Methods and apparatus contemplate: an output transformer having at least first and second separate primary windings and at least one secondary winding, each winding including a first (in phase) end and a second (out of phase) end; at least first and second active elements, each having at least a pair of power terminals and a control terminal, one power terminal of each active element being coupled to a common node; and a switching circuit operable to change a circuit configuration of the first and second primary windings and the active elements between a class A mode and a class A/B mode.

19 Claims, 6 Drawing Sheets

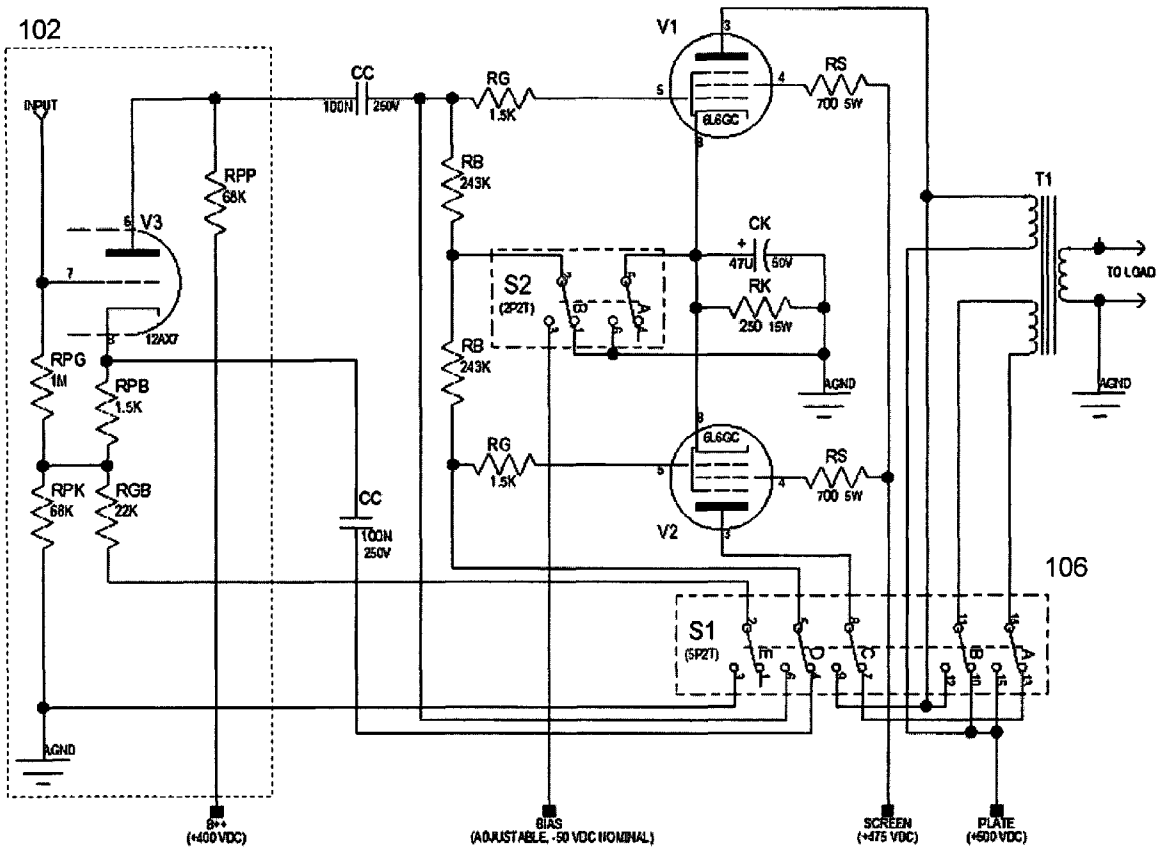


FIG. 1

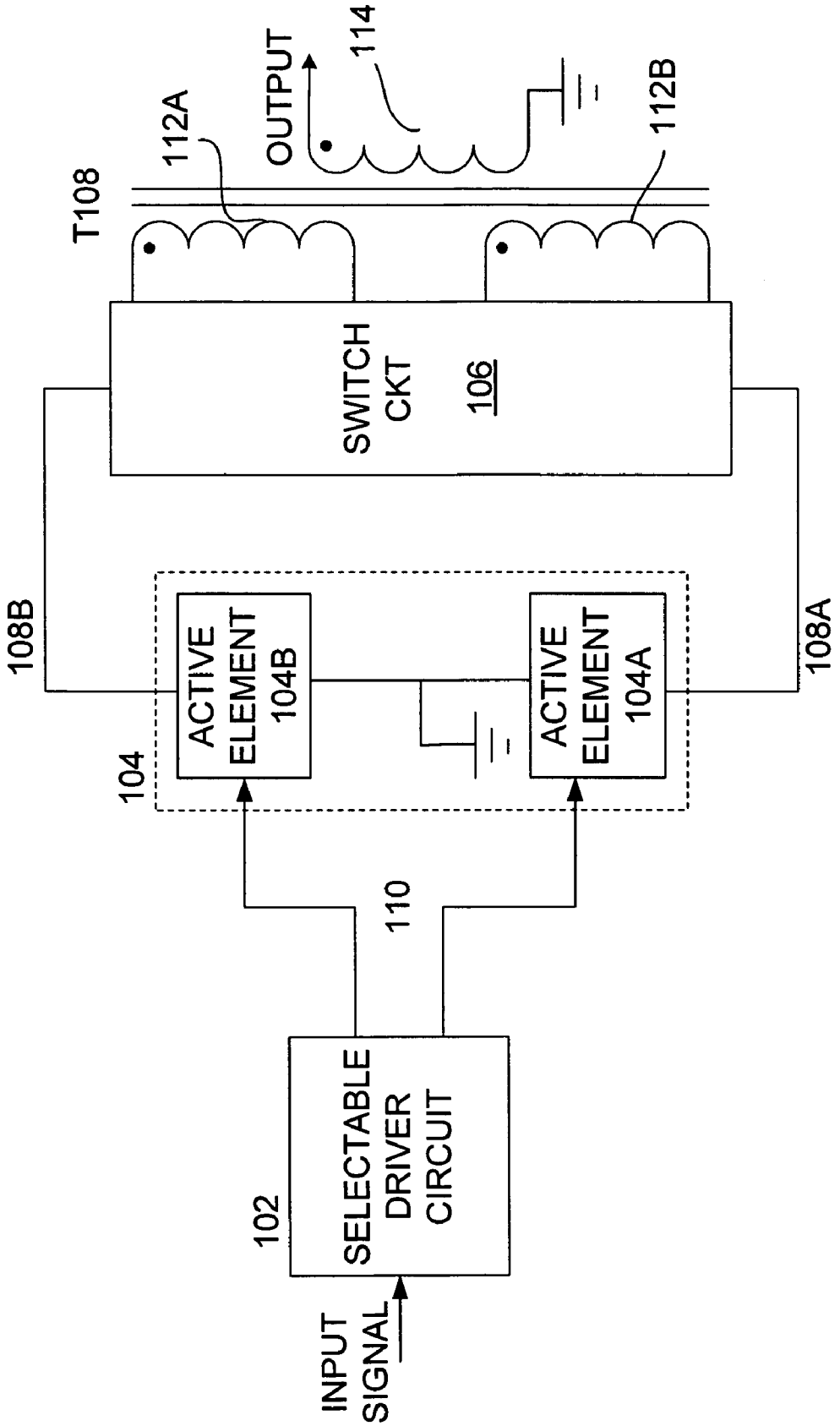

T108
112A
OUTPUT
114
112B
SWITCH CKT
106
108B
108A
ACTIVE ELEMENT 104B
ACTIVE ELEMENT 104A
104
110
SELECTABLE DRIVER CIRCUIT
102
INPUT SIGNAL

FIG. 2A

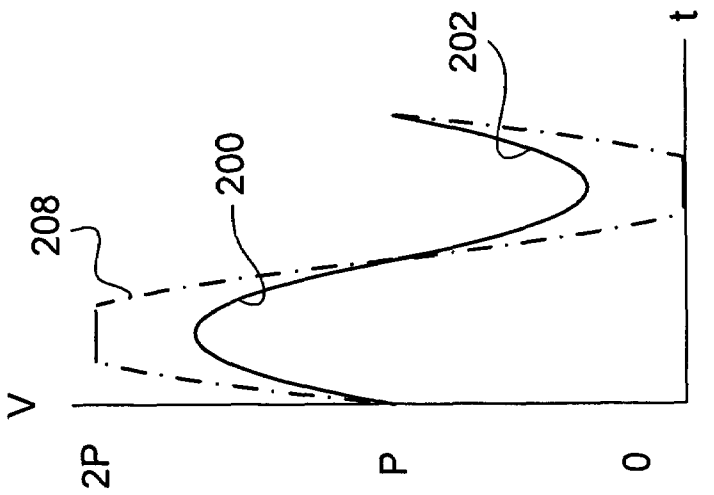


FIG. 2B

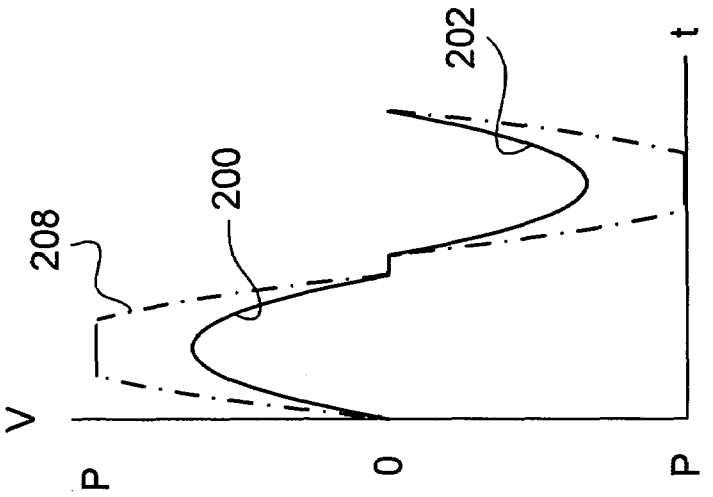


FIG. 3

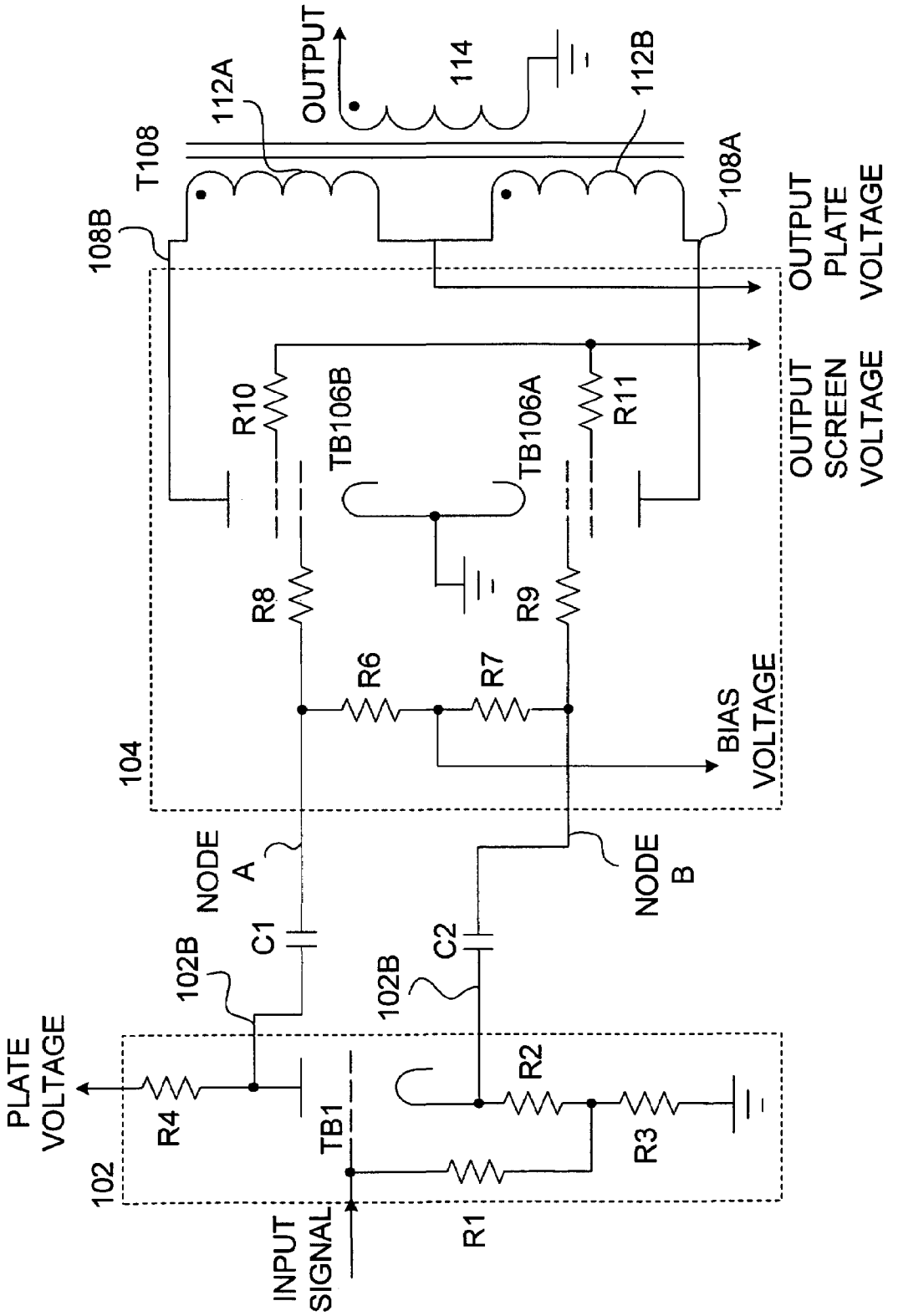

OUTPUT
114
112B
112A
T108
108B
108A
OUTPUT PLATE VOLTAGE
OUTPUT SCREEN VOLTAGE
R10
TB106B
TB106A
R11
R8
R9
R6
R7
BIAS VOLTAGE
104
NODE A
NODE B
C1
C2
102B
102B
PLATE VOLTAGE
R4
R2
TB1
R3
102
R1
INPUT SIGNAL

FIG. 4

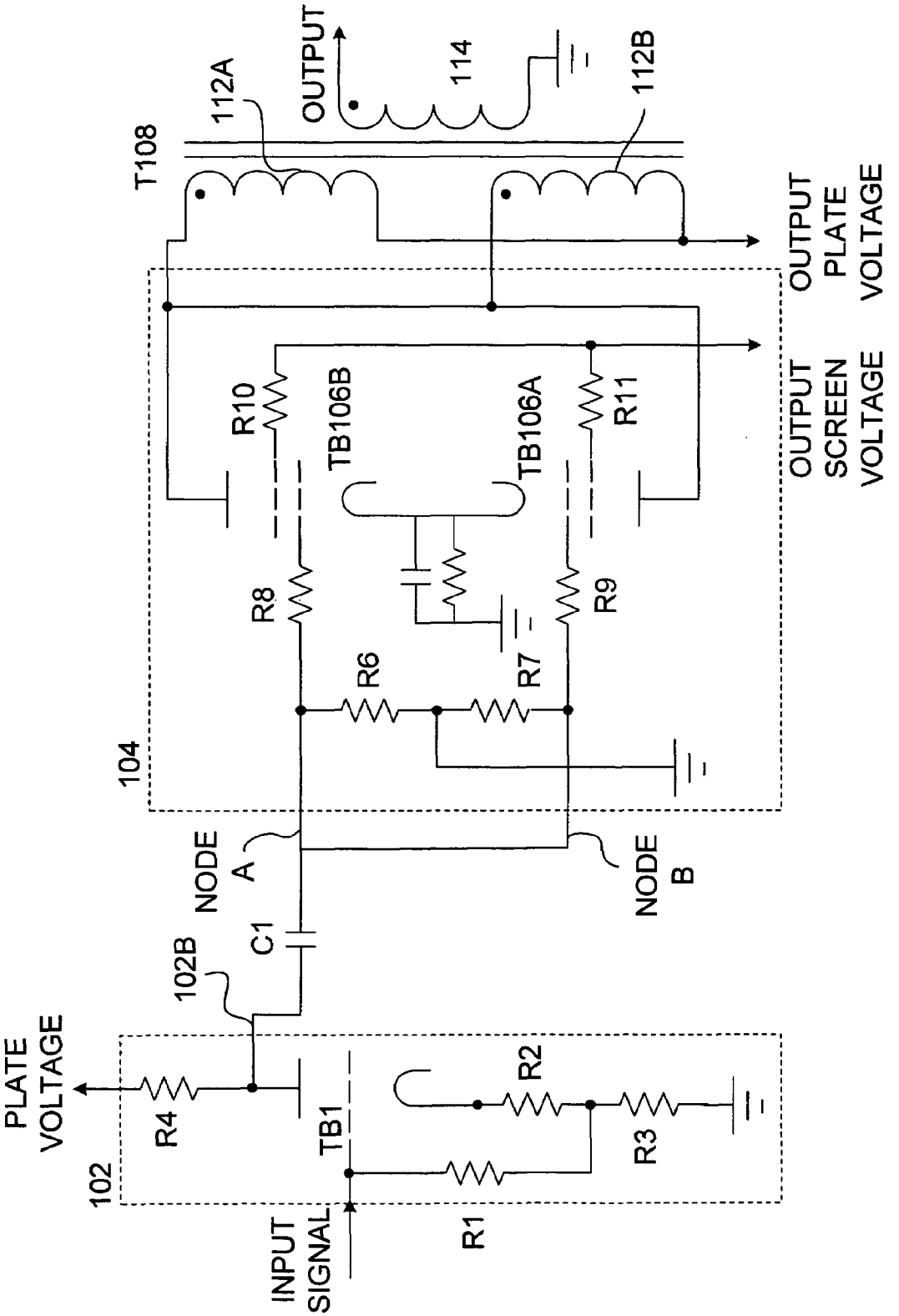

T108
112A
OUTPUT
114
112B
OUTPUT PLATE VOLTAGE
OUTPUT SCREEN VOLTAGE
R10
TB106B
TB106A
R11
R8
R6
R7
R9
104
NODE A
NODE B
C1
102B
PLATE VOLTAGE
R4
TB1
R2
R3
102
R1
INPUT SIGNAL

FIG. 5

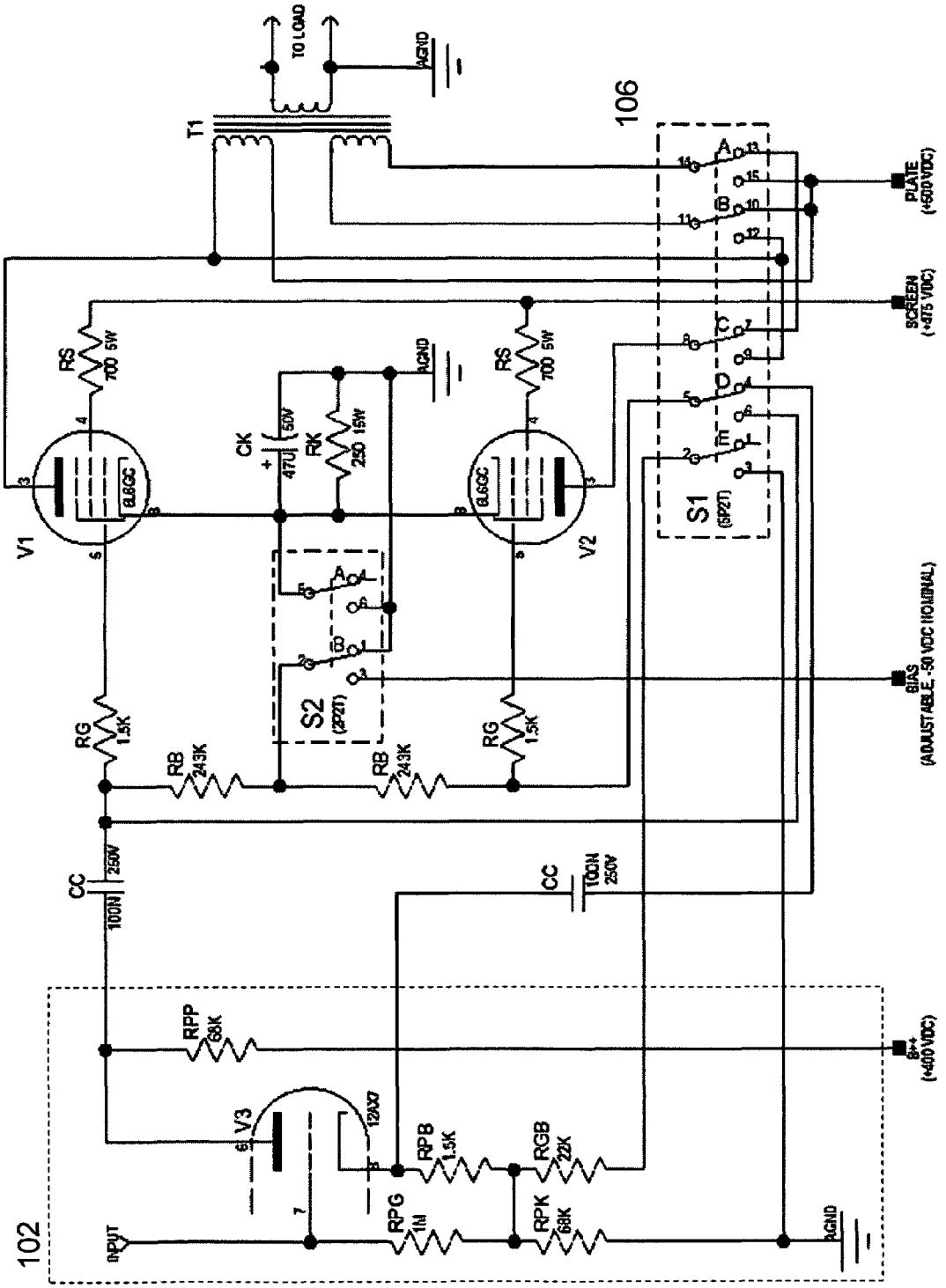
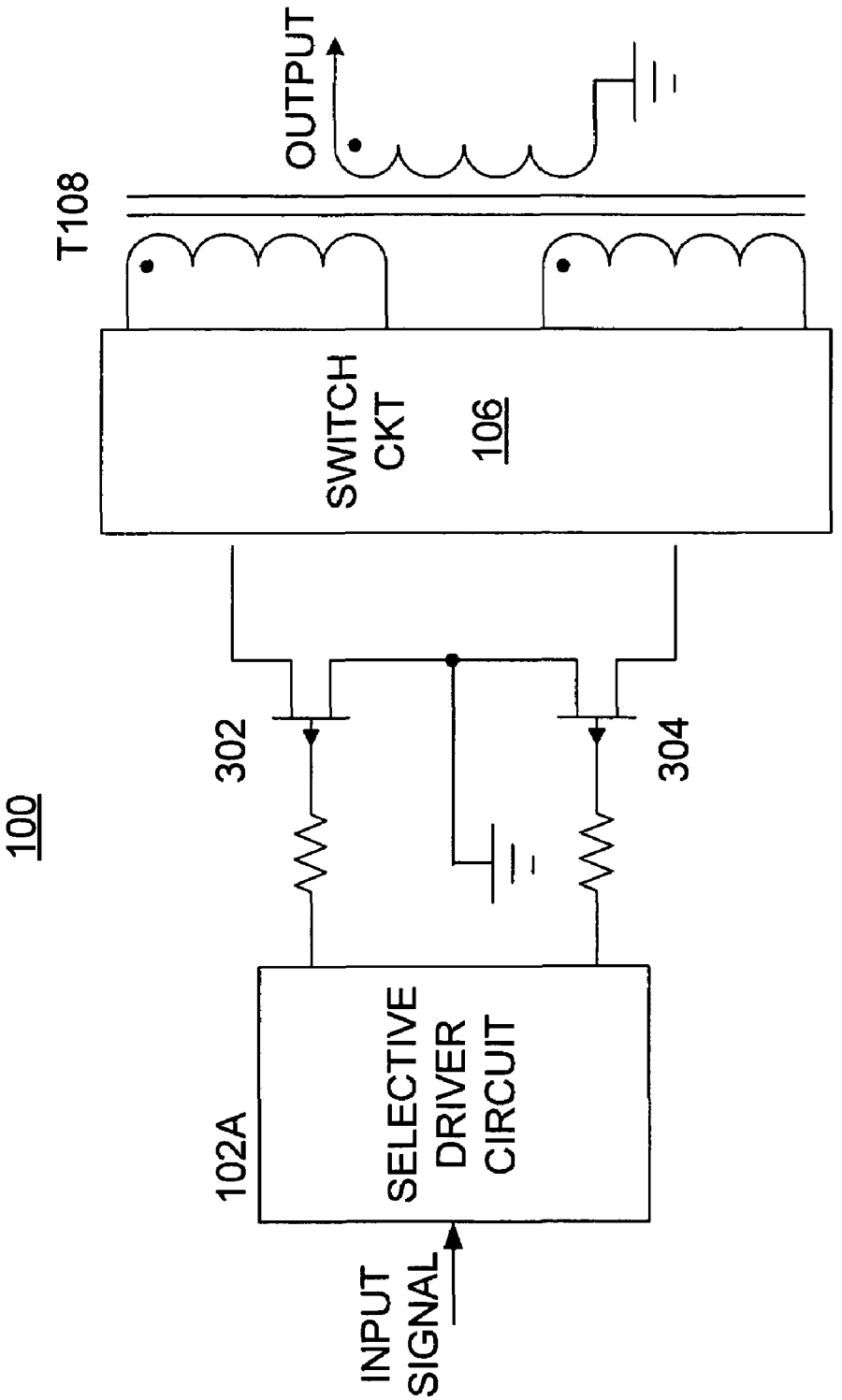

T1
TO LOAD
AGND
106
PLATE (+600 VDC)
SCREEN (+475 VDC)
BIAS (ADJUSTABLE, -50 VDC NOMINAL)
B+ (+400 VDC)
V1
V2
V3
6L6GC
12AX7
S1 (3P2T)
S2 (2P2T)
RS 700 5W
RK 250 15W
CK 47U 50V
RG 1.5K
RB 243K
CC 100N 250V
RPP 68K
RPB 1.5K
RGB 22K
RPG 1M
RPK 68K
INPUT
102

FIG. 6


100
T108
OUTPUT
SWITCH CKT
106
302
304
102A
SELECTIVE DRIVER CIRCUIT
INPUT SIGNAL

METHODS AND APPARATUS FOR SWITCHING BETWEEN CLASS A AND A/B OPERATION IN A POWER AMPLIFIER

BACKGROUND OF THE INVENTION

The present invention relates to methods and apparatus for selectively changing a circuit configuration of a power amplifier stage, e.g., for a guitar amplifier, between class A and class A/B.

Designers of guitar amplifiers, up until the late 1950's, focused on creating inexpensive amplifiers with very little distortion. This was not an easy task as solid state devices were not generally available and nearly all amplifiers were designed and built using vacuum tubes. Although tube amplifiers inherently have more distortion than solid state amplifiers, the early amplifier pioneers tried in vain to produce amplifiers with little or no distortion. Most of their designs had a high order of distortion, especially second harmonic distortion, because of the fact that most used a Class A power amplifier topology.

In the context of electric guitar amplification, the existence of harmonic distortion in the amplifier is not undesirable. Indeed, it has been generally thought that even order harmonics are pleasing to the ear, (especially the second harmonic), while odd order harmonics are thought to sound "raucous," "raspy," and unpleasant, especially the third and fifth harmonics. The desirability of even order harmonics appears to hold even in fairly high ratios to the normal (undistorted) signal.

As most rock guitar players use solid body guitars, which provide relatively little resonance, most of the harmonics associated with the characteristic sounds identifiable as an electric guitar actually come from the amplifier and not the guitar. The harmonics introduced by the guitar amplifier differentiate one guitar system (e.g., guitar and amplifier combination) from another, thereby giving each system its own "personality." Thus, guitar amplification has become a niche technology within the broader universe of the audio amplification arts. What sets a guitar amplifier apart from an amplifier found in, for example, a sound system or a home stereo is that the latter seeks to reproduce sounds as closely as possible to the input signal, while the former significantly alters the sound and is, in essence, an extension of the instrument and a part of an overall guitar system.

For efficiency, transformer design, and other cost considerations, most high-power tube type guitar amplifiers utilize push-pull output stages operating in class A/B. The A/B class dictates that the output signal is shared by two or more output tubes which are driven by signals that are equal in magnitude and 180 degrees out of phase. In contrast, class A amplifiers are typically single-ended and are driven from a single drive signal. When driven into clipping, a class A amplifier produces an output rich in second order harmonics, which as discussed above is generally considered to be desirable. Unfortunately, a class A/B power amplifier can produce an output rich in odd order harmonics (in addition to some even order harmonics), which is not considered as desirable.

While the design of a class A/B amplifier in accord with conventional wisdom may be acceptable to some users, many guitar players may find the odd-order harmonic content objectionable. It would be desirable, therefore, to provide an amplifier that can be selectively switched between class A and class A/B operation so that either of the following results can be obtained: (i) efficient amplification (at the expense of harmonic content); or (ii) desirable harmonic content (at the expense of efficiency). Finding circuit solutions to achieve selective switching between class A and class A/B operation is not trivial. Indeed, cost, product size and circuit performance may be significantly impacted by the circuit implementation and control methodology employed. It has been discovered that desirable results in cost, size and performance may be achieved employing one or more aspects of the various embodiments of the invention as described and claimed herein.

SUMMARY OF THE INVENTION

In accordance to one or more aspects of the present invention, methods and apparatus provide for: providing an output transformer having at least first and second separate primary windings and at least one secondary winding, each winding including a first (in phase) end and a second (out of phase) end; providing at least first and second active elements, each having at least a pair of power terminals and a control terminal; and selectively changing a circuit configuration of the first and second primary windings and the active elements between a class A mode and a class A/B mode.

Various embodiments of the invention may include an apparatus, comprising: an output transformer having at least first and second separate primary windings and at least one secondary winding, each winding including a first (in phase) end and a second (out of phase) end; at least first and second active elements, each having at least a pair of power terminals and a control terminal, one power terminal of each active element being coupled to a common node; and a switching circuit operable to change a circuit configuration of the first and second primary windings and the active elements between a class A mode and a class A/B mode.

The switching circuit may be operable to couple the first and second primary windings in series when in the class A/B mode. For example, the switching circuit may be operable to couple the active elements and the first and second primary windings in a push-pull output configuration when in the class A/B mode. Preferably, the switching circuit is operable such that in the class A/B mode, the other power terminal of the first active element is coupled to the first end of the first primary winding, the other power terminal of the second active element is coupled to the second end of the second primary winding, and the second end of the first primary winding is coupled to the first end of the second primary winding.

Additionally, the switching circuit may be operable to couple the first and second primary windings in parallel when in the class A mode. Additionally, the switching circuit is preferably operable to couple the first and second active elements in parallel when in the class A mode. For example, the switching circuit may be operable to couple the first and second active elements and the first and second primary windings in a single-ended output configuration when in the class A mode. Preferably, the switching circuit is operable such that in the class A mode, the first and second primary windings are coupled in parallel, and the first and second active elements are coupled in parallel such that the other power terminals thereof are coupled to the first ends of the primary windings.

The apparatus may also include a driver circuit operable to receive an input signal and produce: first and second drive signals therefrom, each about 180 degrees out of phase with respect to the other, for the respective control terminals of the first and second active elements when in the class A/B mode; and a single-phase drive signal for both the control

terminals of the first and second active elements when in the class A mode. Preferably, the switching circuit is operable to control the configuration of the driver circuit into the respective class A/B and class A modes.

The switching circuit is preferably user-controllable to permit the user to select the mode of operation.

In an alternative embodiment, the active elements may be tubes and the apparatus may further include a selectively configurable bias circuit operable to selectively provide: (i) self bias to the control terminals of the first and second tubes; or (ii) a fixed negative bias to the control terminals of the first and second tubes.

Other aspects, features, and advantages of the present invention will be apparent to one skilled in the art from the description herein taken in conjunction with the accompanying drawings.

DESCRIPTION OF THE DRAWINGS

For the purposes of illustration, there are forms shown in the drawings that are presently preferred, it being understood, however, that the invention is not limited to the precise arrangements and instrumentalities shown.

FIG. **1** is a block diagram of an amplifier circuit that is operable to provide selective operation in class A or class A/B modes in accordance with one or more aspects of the present invention;

FIGS. **2**A–B are graphical representations of the operation of the circuit of FIG. **1** in each mode, including clipping distortion;

FIG. **3** is a schematic diagram of one embodiment of the circuit of FIG. **1** in the class A/B mode of operation;

FIG. **4** is a schematic diagram of one embodiment of the circuit of FIG. **1** in the class A mode of operation;

FIG. **5** is a more detailed schematic diagram of one embodiment of the circuit of FIG. **1**; and

FIG. **6** is a partial block diagram and schematic diagram of an alternative embodiment of a solid state output circuit suitable for implementing at least a portion of the amplifier circuit of FIG. **1**.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

With reference to the drawings wherein like numerals indicate like elements, there is shown in FIG. **1** a block diagram of an amplifier circuit **100** that is operable to provide selectability in the topology class of the amplifier: between class A operation and class A/B operation in accordance with one or more aspects of the present invention. The amplifier circuit **100** includes a selectable driver circuit **102**, a power amplifier stage **104**, a switching circuit **106**, and an output transformer stage **108**.

The selectable driver circuit **102** is preferably operable to receive an input signal (such as from upstream circuitry of an electric guitar preamplifier) and to produce one or more drive signals **110** suitable for biasing at least the active components of the power amplifier stage **104**. As will be discussed in more detail herein below, the selectable driver circuit **102** is operable to produce a single-phase drive signal **110** for class A operation or first and second drive signals (each about 180 degrees out of phase) for class A/B operation, depending on the user selectable operational mode.

In the embodiment shown in FIG. **1**, the power amplifier **104** includes a first active element **104**A and a second active element **104**B. Those skilled in the art of power amplifier design will appreciate that there may be numerous components within each of the active elements **104**A, **104**B, although for the purposes of brevity and clarity, the active elements **104**A, **104**B will be referred to herein in the singular. As will be discussed in more detail below, depending on the state of the switching circuit, which bridges the connections between the power amplifier stage **104** and the output stage **108**, the circuit connections involving the active elements **104**A, **104**B are adjustable in accordance with the selected mode of operation.

The output stage **108** preferably includes a multi-winding transformer T**108**, which includes at least first and second separate primary windings **112**A, **112**B and at least one secondary winding **114**. Each winding **112**A, **112**B, and **114** preferably includes a first (in phase) end and a second (out of phase) end, where the in phase ends are indicated using conventional "dot" labeling. It is a notable feature of this embodiment of the present invention that the transformer T**108** includes two separate primary windings **112**A and **112**B; indeed, as will be discussed below, this provide advantageous cost, size and performance advantages.

In accordance with one or more aspects of the present invention, the switching circuit **106** is preferably operable to change the circuit configuration of the first and second primary windings **112**A, **112**B and the active elements **104**A, **104**B between a class A mode and a class A/B mode. This is graphically illustrated in FIGS. **2**A and **2**B. It is assumed for the purposes of discussion that the input signal to the amplifier circuit **100** is a sine wave having substantially zero DC content. The graphs of FIGS. **2**A–**2**B represent the output signal produced by the output stage **108** in response to such sine wave. In FIG. **2**A, which illustrates class A operation, the upward swing **200** and downward swing **202** of the output signal are above zero, symmetrical about potential P, and peak at **2**P and zero, respectively. When the output signal is driven into clipping **208**, the resulting distortion is rich in even-order harmonics, particularly second order harmonics. In FIG. **2**B, which illustrates class A/B operation, the upward swing **200** of the output signal is above zero, the downward swing **202** is below zero, and they peak at P. Note that class A/B operation usually includes some cross-over distortion as the waveform transitions through zero. When the output signal is driven into clipping, the resulting distortion includes even-order harmonics and odd-order harmonics.

With reference to FIG. **3**, the switching circuit **106** is preferably operable to couple the active elements **104**A, **104**B and the first and second primary windings **112**A, **112**B in a push-pull output configuration when the class A/B mode is selected. FIG. **3** illustrates the circuit topology after the switching circuit has been activated in the class A/B mode. By way of example, the active elements **104**A, **104**B are shown as being implemented using vacuum tubes TB**104**A, TB**104**B. The tubes TB**104**A, TB**104**B each have at least a pair of power terminals (plate and cathode), and at least one control terminal (one or more grids). The cathodes of each tube TB**104**A, TB**104**B are coupled to a common node, such as ground.

Notably, the switching circuit **106** operates such that, in the class A/B mode, the primary windings **112**A, **112**B are coupled in series with the active elements TB**104**A, TB**104**B, which are also in series. In particular, the plate terminal of the tube TB**104**A is coupled to the first end of the first primary winding **112**A, the plate terminal of the other tube TB**104**B is coupled to the second end of the second primary winding **112**B, and the second end of the first primary winding **112**A is coupled to the first end of the second primary winding **112**B. The common connection node of the first and second primary windings **112**A, **112**B of the transformer T**108** is coupled to the output plate voltage supply, which may be on the order of about 150–500 VDC. Those skilled in the art will recognize that that the

series coupled primary windings **112**A, **112**B of the transformer T**108** represent a substantial departure from the conventional transformer configuration for class A/B power amplifiers; indeed, conventional wisdom dictates that a center-tapped single primary winding is used.

The respective grids of the tubes TB**104**A, TB**104**B are biased at a potential below the respective cathodes by way of a negative bias voltage and bias resistors R**6**, R**7**, R**8** and R**9**. The screens of the tubes TB**104**A, TB**104**B are biased by way of an output screen voltage supply and resistors R**10**, R**11**. It is noted that the screens are preferably biased slightly lower than the plate voltage of the tubes TB**104**A, TB**104**B, to as low as about one half of the plate voltage. The output signal is taken at the secondary winding **114** of the transformer T**108**.

In operation, the grids of the tubes TB**104**A, TB**104**B receive the drive signals on node A and node B, respectively. Assuming a sine wave input signal, the drive signals on nodes A and B will be sine waves 180 degrees out of phase with one another. Thus, when the sine wave on node A is positive going, tube TB**104**A will be biased ON and draw current through the primary winding **112**A of the transformer T**108** in proportion with the magnitude of the node A drive signal. At the same time, the sine wave on node B will be negative going and the tube TB**104**B will be biased OFF. This results in a positive going portion of a sine wave on the output of the transformer T**108**. When the sine wave on node A is negative going, the sine wave on node B is positive going and the tube TB**104**B will be biased ON and draw current through the other primary winding **112**B of the transformer T**108** in proportion with the magnitude of the node B drive signal. The negative going sine wave on node A will bias the tube TB**104**B OFF. This results in a negative going portion of a sine wave on the output of the transformer T**108**.

As discussed above, the selectable driver circuit **102** is preferably operable to produce first and second drive signals **102**A, **102**B (each about 180 degrees out of phase from one another) for class A/B operation. As shown, the phase inverter **102** may be implemented utilizing a tube TB**1**, and a plurality of resistors R**1**–R**4**. An input resistor R**1** is coupled between a grid of the tube TB**1** and a common node of a resistor divider circuit formed by resistors R**2**, R**3** coupled in series from the cathode of the tube TB**1** to ground. The plate of the tube TB**1** is coupled to a plate voltage through resistor R**4**. The plate voltage may be on the order of about 150–400 VDC. Output from the phase inverter **102** is taken at the cathode and the plate, respectively.

The basic operation of the phase inverter **102** in class A/B operation is as follows: Positive and negative swings in the input signal vary the grid voltage with respect to the cathode voltage such that corresponding variations in the current through the tube TB**1** are achieved. The current gain through the tube TB**1** is inversely proportional to the combined series resistance of R**2** and R**3**. The variations in the current through the tube TB**1** result in a varying voltage across R**4** (the output of which is taken at the plate) and a varying voltage across the combined resistance of R**2** and R**3** (the output of which is taken at the cathode). Assuming that resistor R**4** is of a value substantially equal to the combined resistances of resistors R**2** and R**3**, then the respective magnitudes of the first and second drive signals on lines **102**A and **102**B will be balanced, although these drive signals will be 180° out of phase with respect to one another. Referring again to FIG. **2**B, when the drive signals on lines **102**A, **102**B are balanced, the output signal includes a positive going portion **200** and a negative going portion **202** that are balanced and symmetrical about zero voltage potential.

With reference to FIG. **4**, the switching circuit **106** is preferably operable to couple the active elements **104**A, **104**B and the first and second primary windings **112**A, **112**B in a single-ended output configuration when the class A mode is selected. FIG. **4** illustrates the circuit topology after the switching circuit **106** has been activated in the class A mode. In particular, the first and second primary windings **112**A, **112**B are coupled in parallel, and the tubes TB**104**A, TB**104**B are coupled in parallel such that the plate terminals thereof are coupled to the first ends of the primary windings **112**A, **112**B. Those skilled in the art will recognize that the parallel coupled primary windings **112**A, **112**B of the transformer T**108** represent a substantial departure from the conventional transformer configuration for class A power amplifiers; indeed, conventional wisdom dictates that a single primary winding is used.

The selectable driver circuit **102** is operable to produce a single-phase drive signal on node A for both grids of the tubes TB**104**A, TB**104**B. In the class A mode, the tubes TB**104**A, TB**104**B are preferably self biased. With the above configuration, the tubes T**104**A, T**104**B are biased ON when not driven into clipping (preferably equally sharing current) and current flows (preferably evenly) through both primary windings **112**A, **112**B.

Notably, the circuit topology achieved by the switching circuit **106** in the class A mode results in a substantial impedance match as between the active elements **104**A, **104**B and the primary windings **112**A, **112**B. Indeed, the parallel orientation of the primary windings **112**A, **112**B results in a complex impedance of about one half that of the series configuration in the class A/B mode. Advantageously, the parallel orientation of the active elements **104**A, **104**B in the class A orientation also results in about a halving of the impedance of the series configuration in the class A/B mode. Thus, irrespective of the operating mode, a substantial impedance match as between the active elements **104**A, **104**B and the primary windings **112**A, **112**B is achieved, thereby minimizing attenuation through the amplifier stages. Further, the paralleling of the primary windings **112**A, **112**B in the class A mode ensures full usage of the transformer, including high current handling capability therein, and a high DC saturation level. Thus, the size and cost of the transformer T**108** may be minimized despite supporting the dual modes of operation; indeed, the size of the transformer T**108** may be no greater than a comparable center tapped primary of the conventional class A/B circuit topology.

Reference is now made to FIG. **5**, which is a more detailed schematic diagram of a suitable circuit example for implementing an embodiment of the circuit of FIG. **1**. For the purposes of brevity, a detailed analysis and discussion of all of the circuit components, interconnections, and operations will not be provided here as such will be apparent to those skilled in the art given the description provided herein. Notably, however, the switching circuit **106** may be implemented using a series of single pole double throw (so-called three-way) switches, labeled S**1**. Switches A, B, and C selectively configure the active elements (tubes V**1**, V**2**) and the separate primary windings of the transformer T**1** in either the class A or class A/B configurations. Switches D and E configure the driver circuit **102** for the class A or class A/B configurations.

Additionally, the system may include a switching circuit S**2** for selectively adjusting the biasing scheme for the tubes V**1**, V**2**. In the illustrated switch A and B positions, the tubes V**1**, V**2** are self biased. In the opposite positions, the tubes V**1**, V**2** are fixed biased (although such bias level may be separately adjusted by way of the bias supply).

Those skilled in the art will appreciate that the power amplifier **104** may be implemented utilizing any of the known techniques, such as utilizing tubes, field effect tran-

sistors, bipolar transistors, etc. In this regard, reference is made to FIG. **6**, which illustrates a power amplifier implemented utilizing field effect transistors **302**, **304**. This implementation includes an appropriate driver circuit **102**A that may receive the input signal and produce appropriate gate drive signals to bias the field effect transistors **302**, **304** in an appropriate manner.

Although the invention herein has been described with reference to particular embodiments, it is to be understood that these embodiments are merely illustrative of the principles and applications of the present invention. It is therefore to be understood that numerous modifications may be made to the illustrative embodiments and that other arrangements may be devised without departing from the spirit and scope of the present invention as defined by the appended claims.

The invention claimed is:

1. An apparatus, comprising:

an output transformer having at least first and second separate primary windings and at least one secondary winding, each winding including a first (in phase) end and a second (out of phase) end;

at least first and second active elements, each having at least a pair of power terminals and a control terminal, one power terminal of each active element being coupled to a common node; and

a switching circuit operable to change a circuit configuration of the first and second primary windings and the active elements between a class A mode and a class A/B mode.

2. The apparatus of claim **1**, wherein the switching circuit is operable to couple the first and second primary windings in series when in the class A/B mode.

3. The apparatus of claim **2**, wherein the switching circuit is operable to couple the active elements and the first and second primary windings in a push-pull output configuration when in the class A/B mode.

4. The apparatus of claim **1**, wherein the switching circuit is operable such that in the class A/B mode, the other power terminal of the first active element is coupled to the first end of the first primary winding, the other power terminal of the second active element is coupled to the second end of the second primary winding, and the second end of the first primary winding is coupled to the first end of the second primary winding.

5. The apparatus of claim **1**, wherein the switching circuit is operable to couple the first and second primary windings in parallel when in the class A mode.

6. The apparatus of claim **5**, wherein the switching circuit is operable to couple the first and second active elements in parallel when in the class A mode.

7. The apparatus of claim **5**, wherein the switching circuit is operable to couple the first and second active elements and the first and second primary windings in a single-ended output configuration when in the class A mode.

8. The apparatus of claim **1**, wherein the switching circuit is operable such that in the class A mode, the first and second primary windings are coupled in parallel, and the first and second active elements are coupled in parallel such that the other power terminals thereof are coupled to the first ends of the primary windings.

9. The apparatus of claim **1**, further comprising a driver circuit operable to receive an input signal and produce:

first and second drive signals therefrom, each about 180 degrees out of phase with respect to the other, for the respective control terminals of the first and second active elements when in the class A/B mode; and

a single-phase drive signal for both the control terminals of the first and second active elements when in the class A mode.

10. The apparatus of claim **9**, wherein the switching circuit is operable to control the configuration of the driver circuit into the respective class A/B and class A modes.

11. The apparatus of claim **10**, wherein:

the switching circuit is user-controllable to permit the user to select the mode of operation; and

the switching circuit is operable to substantially simultaneously configure the driver circuit, the transformer and the active elements into the selected mode.

12. The apparatus of claim **1**, wherein the switching circuit is user-controllable to permit the user to select the mode of operation.

13. The apparatus of claim **1**, wherein the active elements are taken from the group consisting of tubes, field effect transistors and bipolar transistors.

14. The apparatus of claim **1**, wherein the active elements are tubes and the apparatus further comprises a selectively configurable bias circuit operable to selectively provide: (i) self bias to the control terminals of the first and second tubes; or (ii) a fixed negative bias to the control terminals of the first and second tubes.

15. A method, comprising:

providing an output transformer having at least first and second separate primary windings and at least one secondary winding, each winding including a first (in phase) end and a second (out of phase) end;

providing at least first and second active elements, each having at least a pair of power terminals and a control terminal; and

selectively changing a circuit configuration of the first and second primary windings and the active elements between a class A mode and a class A/B mode.

16. The method of claim **15**, further comprising coupling the first and second primary windings in series when in the class A/B mode.

17. The method of claim **16**, further comprising coupling the active elements and the first and second primary windings in a push-pull output configuration when in the class A/B mode.

18. The method of claim **15**, further comprising, when in the class A/B mode:

coupling one power terminal of each active element to a common node;

coupling the other power terminal of the first active element to the first end of the first primary winding;

coupling the other power terminal of the second active element to the second end of the second primary winding; and

coupling the second end of the first primary winding to the first end of the second primary winding.

19. The method of claim **15**, further comprising, when in the class A mode, coupling the first and second active elements and the first and second primary windings in a single-ended output configuration such that:

the first and second primary windings are coupled in parallel; and

the first and second active elements are coupled in parallel,

wherein the other power terminals of the first and second active elements are coupled to the first ends of the primary windings.

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