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Grundingh

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(54) **SWITCHED-MODE POWER AMPLIFIER USING LUMPED ELEMENT IMPEDANCE INVERTER FOR PARALLEL COMBINING**

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(21) Appl. No.: **11/787,231**

(57) **ABSTRACT**

(22) Filed: **Apr. 12, 2007**

A switched-mode Class F power amplifier is provided for parallel connection with at least one other like amplifier, within a Chireix architecture, for combining the signals output therefrom. An input component includes at least one active device configured to be alternately switched by a signal input thereto to present an amplified signal corresponding to the input signal and constituting a low output impedance voltage source. A lumped element impedance inverter is provided between the input component and an output resonator component, the impedance inverter being configured for transforming the low output impedance voltage source to instead constitute a high output impedance current source configured for said parallel connection. In accordance with the invention, the negative reactive component values required by the impedance inverter are eliminated and effectively provided by incorporating those values into pre-selected reactive components of the input and output components. Further, a source-drain parasitic capacitance across the active device is eliminated by one or more pre-selected reactive components of the input component, the value(s) of which effectively compensate for the parasitic capacitance.

Related U.S. Patent Documents

Reissue of:

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Appl. No.: **10/615,468**
Filed: **Jul. 8, 2003**

(51) **Int. Cl.**
H03F 3/217 (2006.01)

(52) **U.S. Cl.** **330/251; 330/207 A**

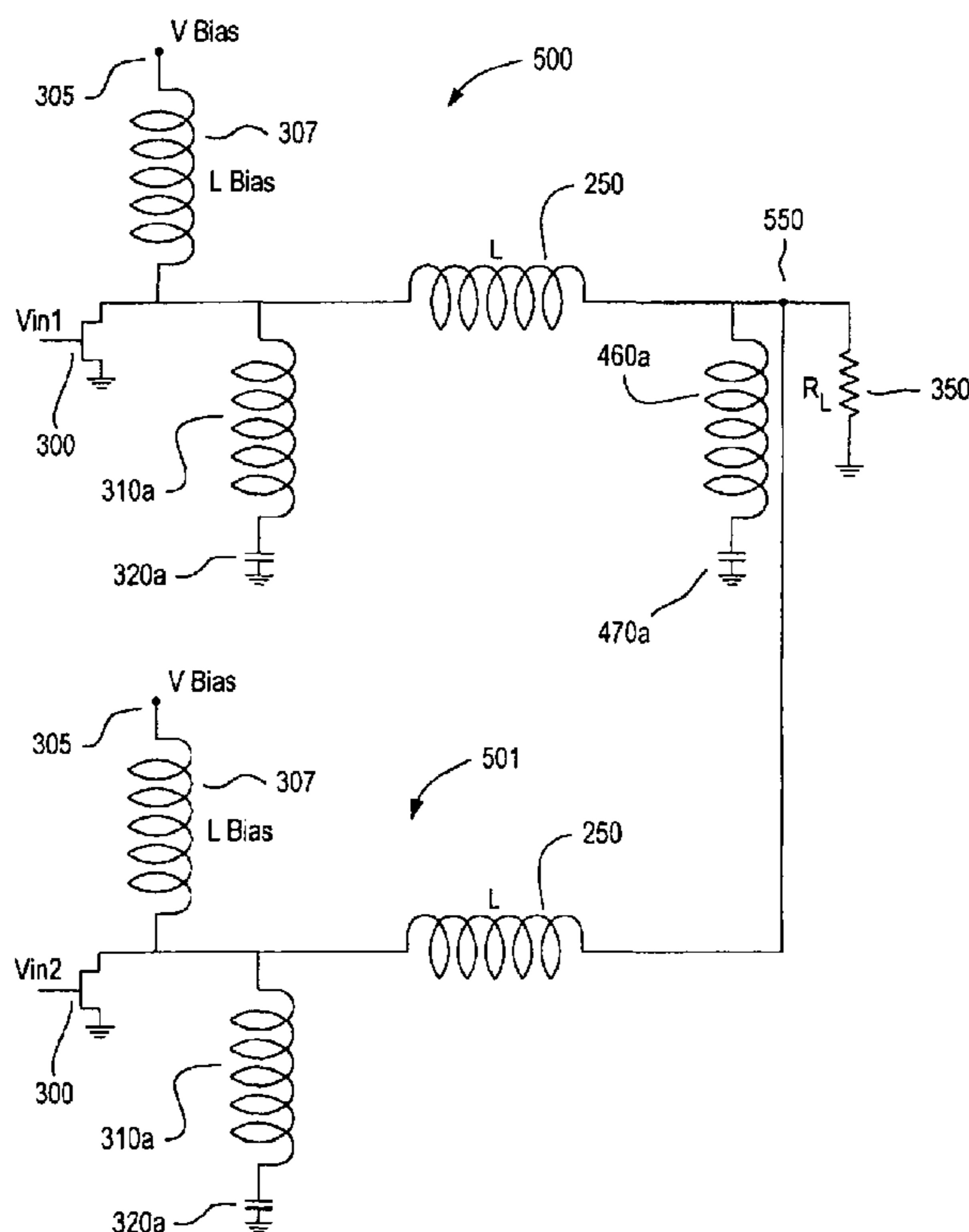
(58) **Field of Classification Search** 330/10,
330/207 A, 251, 292; 333/214
See application file for complete search history.

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22 Claims, 6 Drawing Sheets



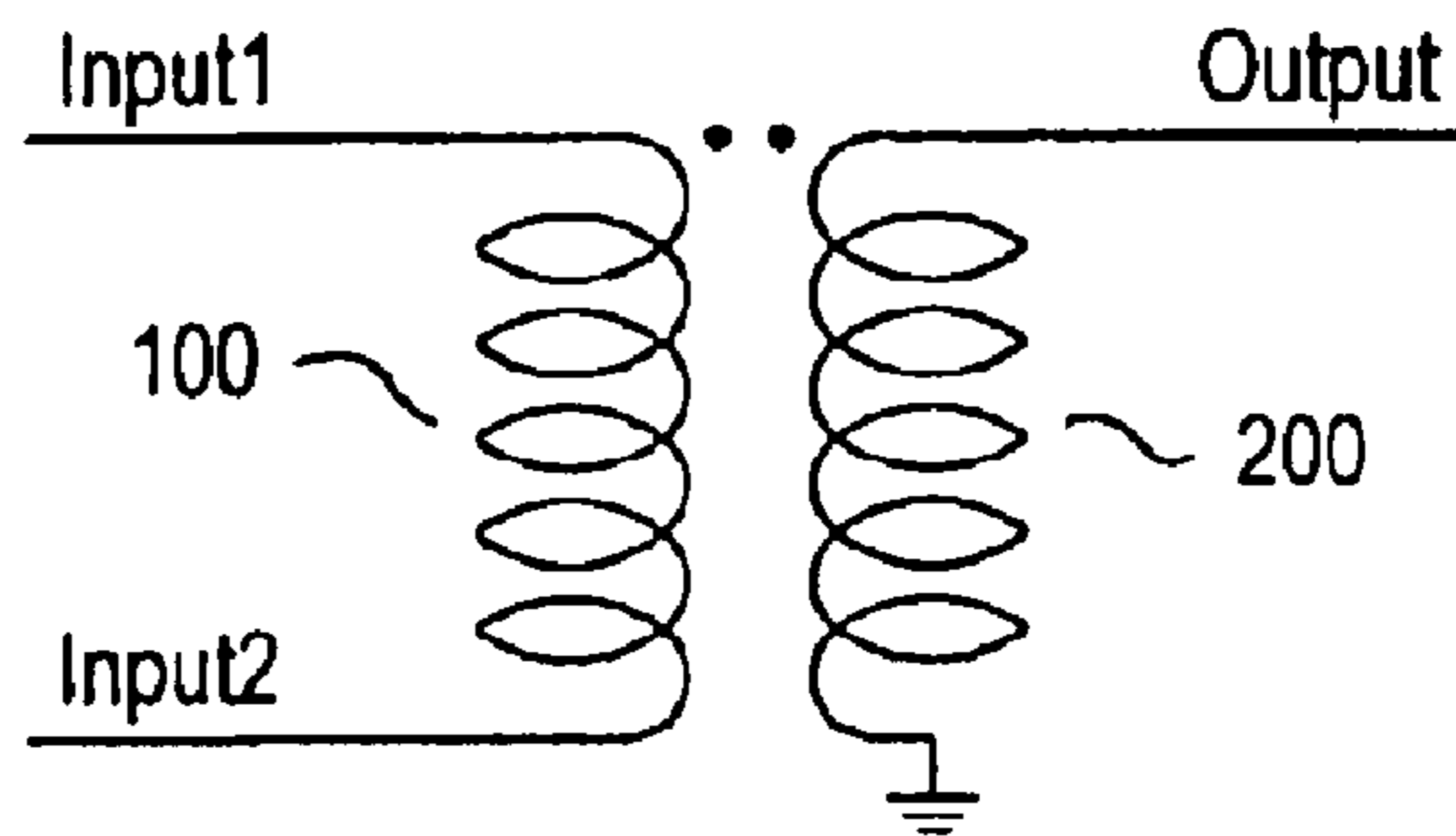


FIG. 1
(Prior Art)

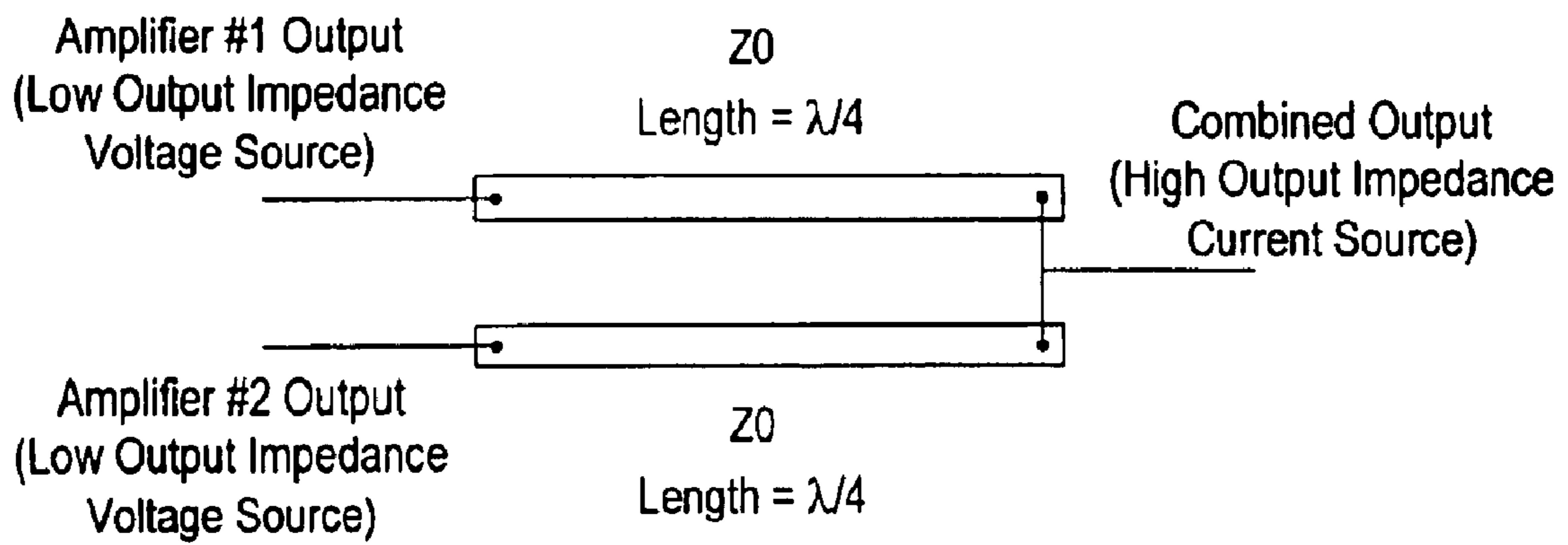


FIG. 2
(Prior Art)

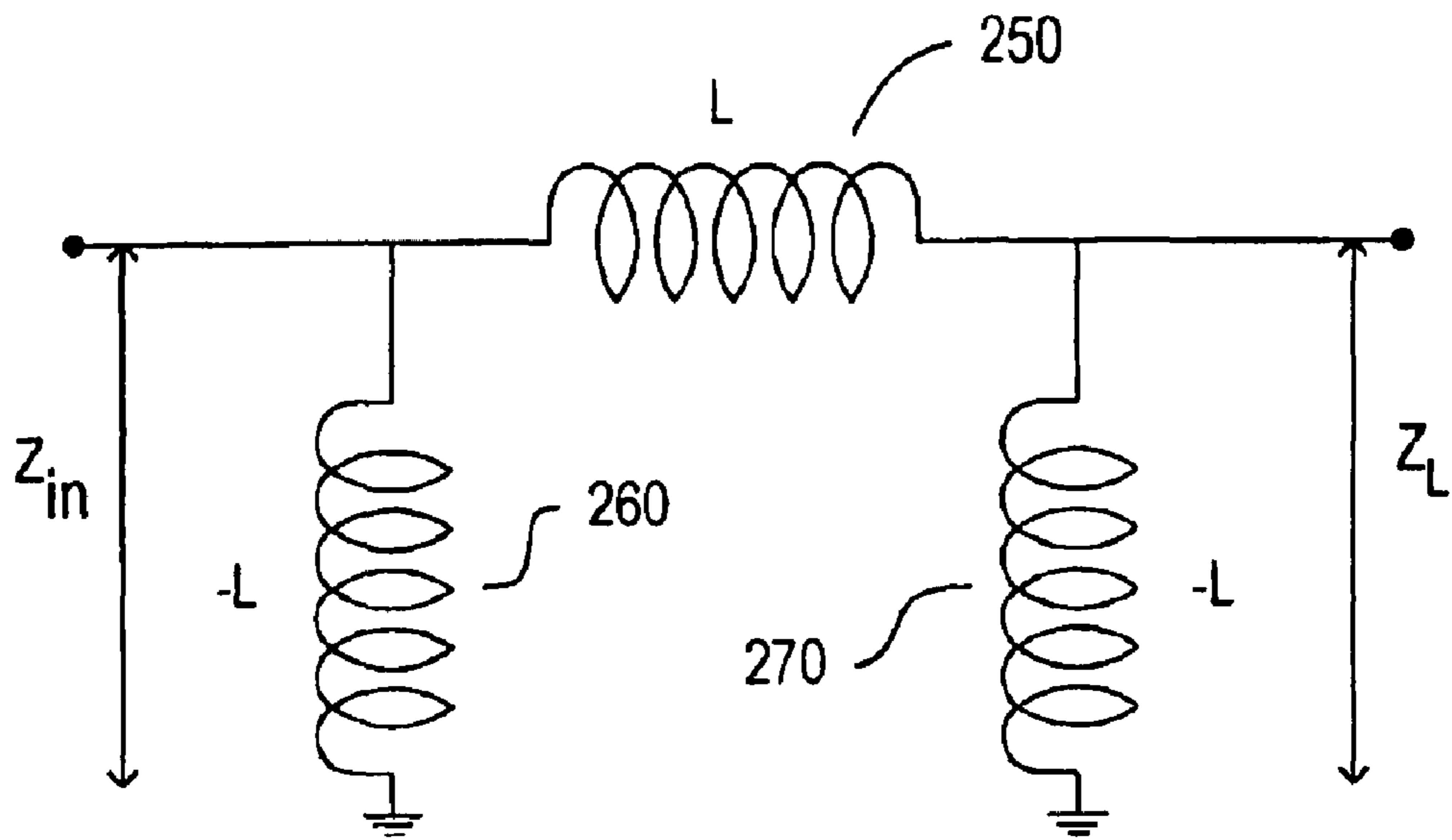


FIG. 3A

(Prior Art)

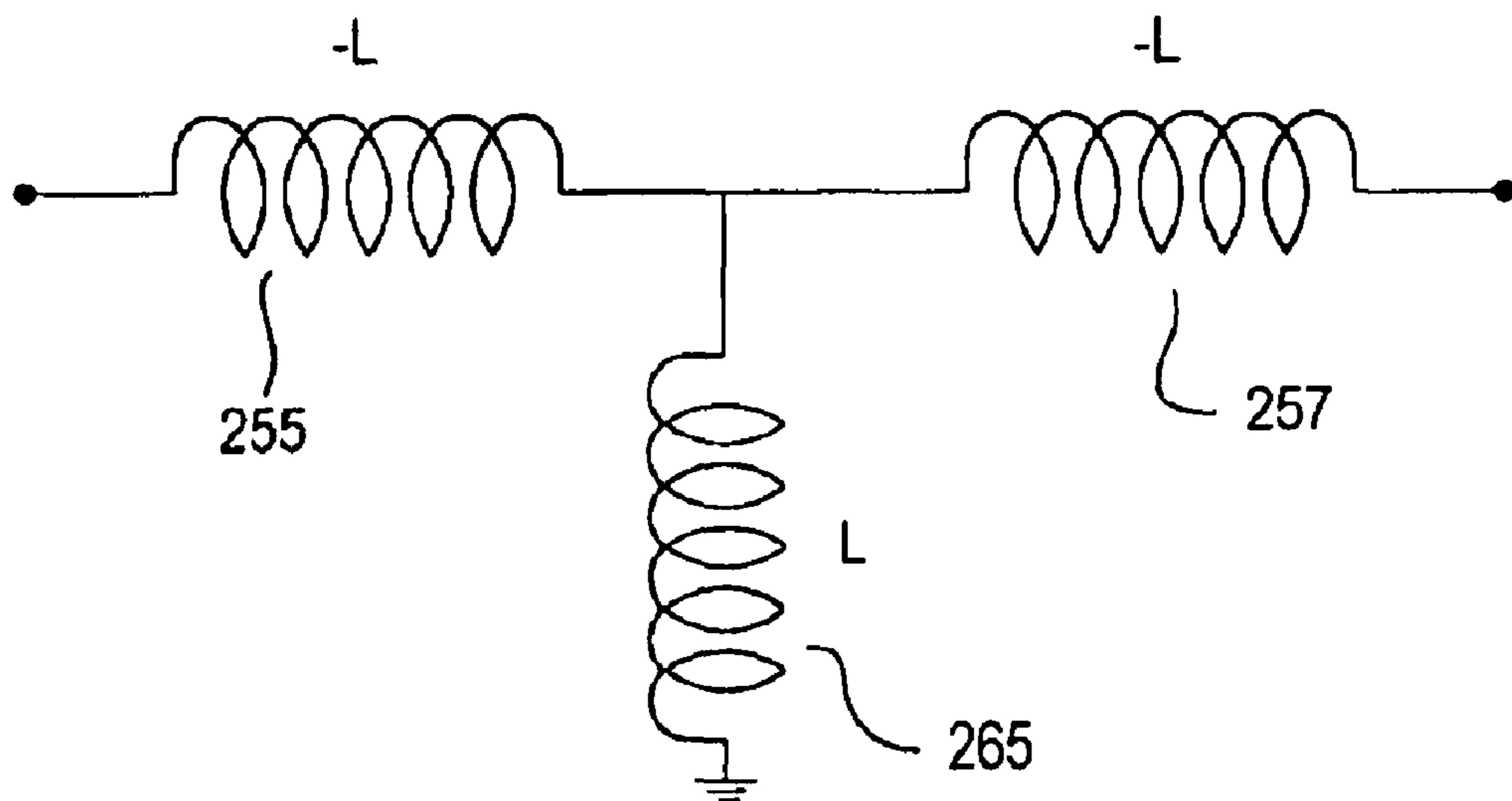


FIG. 3B

(Prior Art)

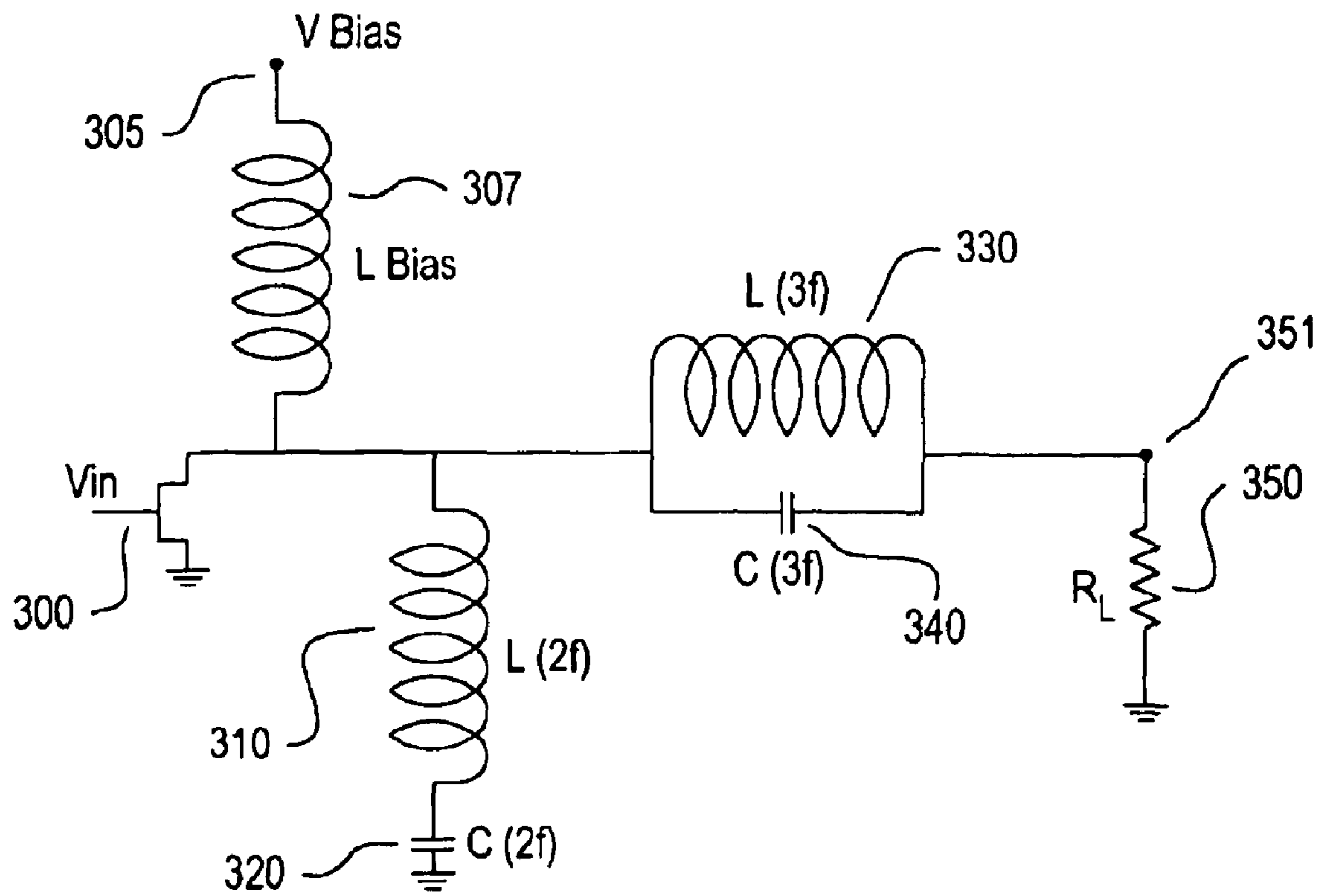


FIG. 4
(Prior Art)

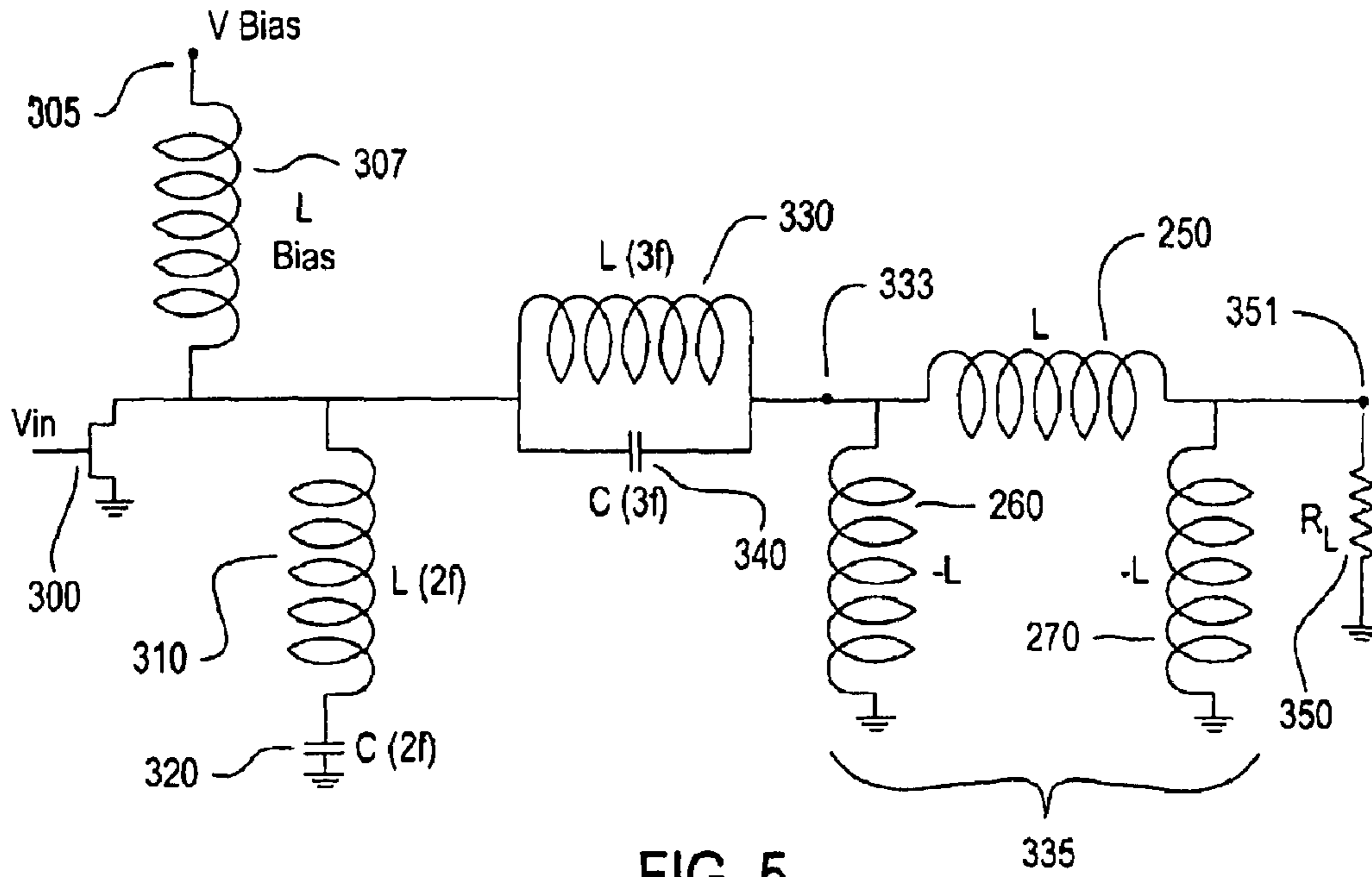


FIG. 5

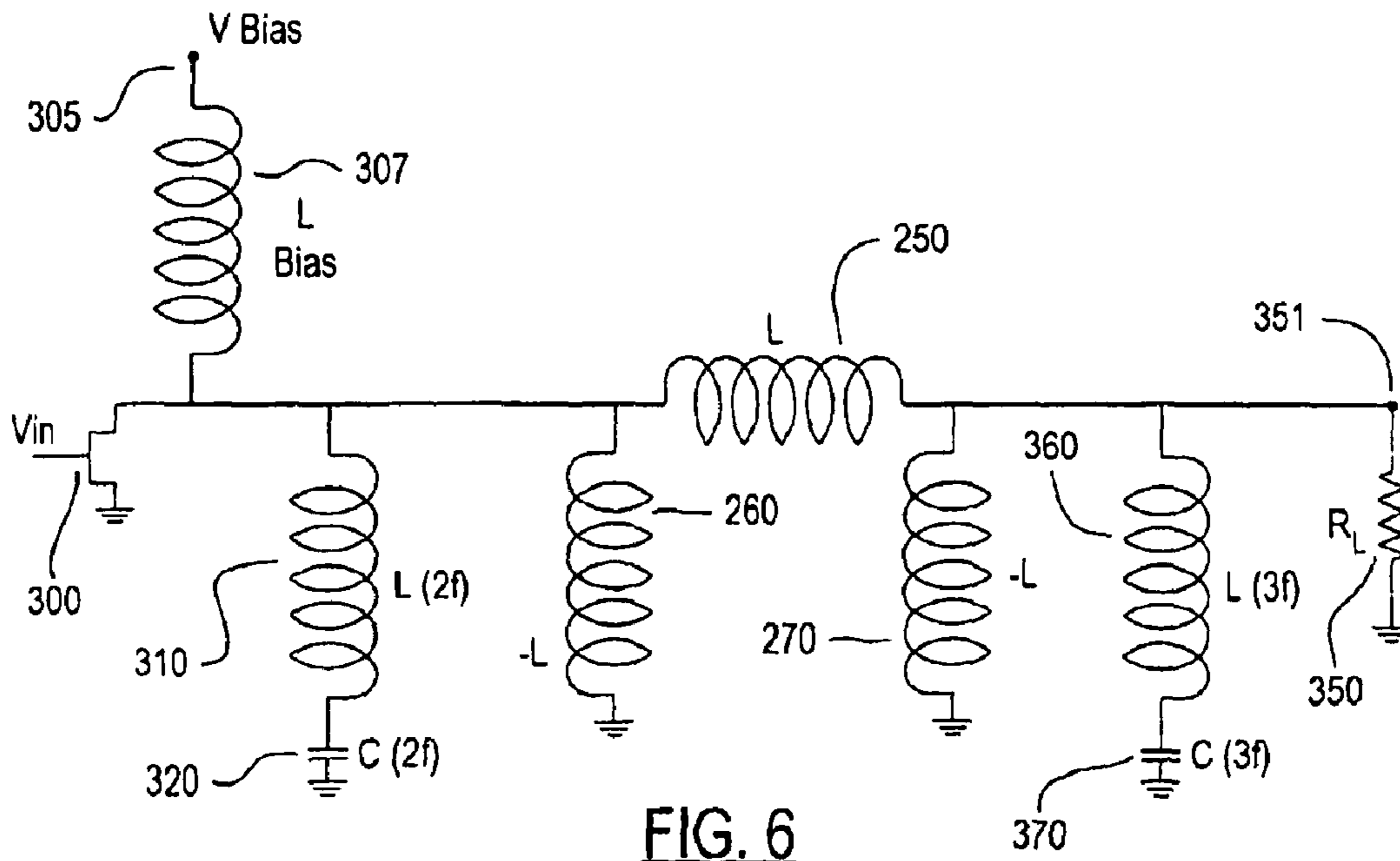


FIG. 6

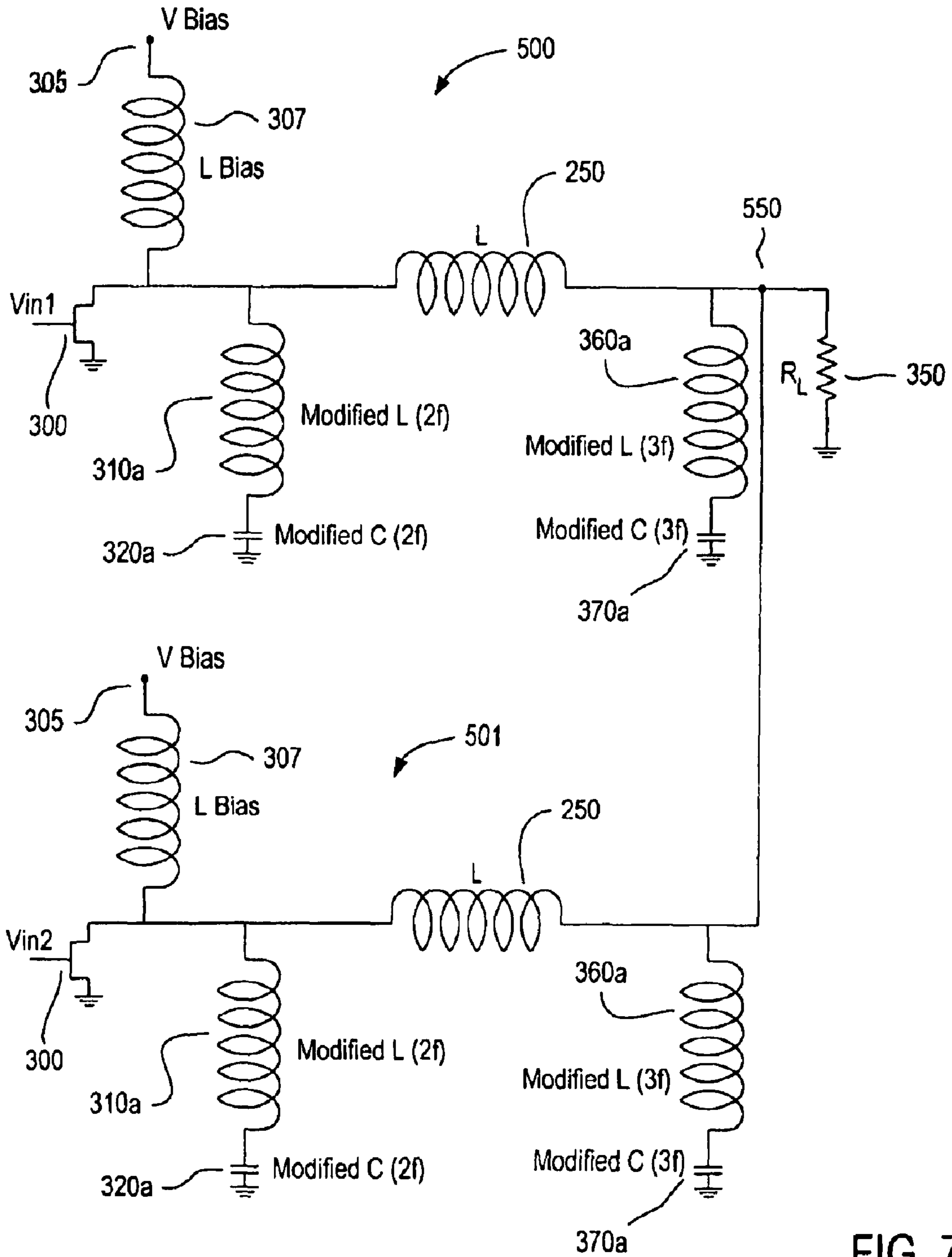


FIG. 7

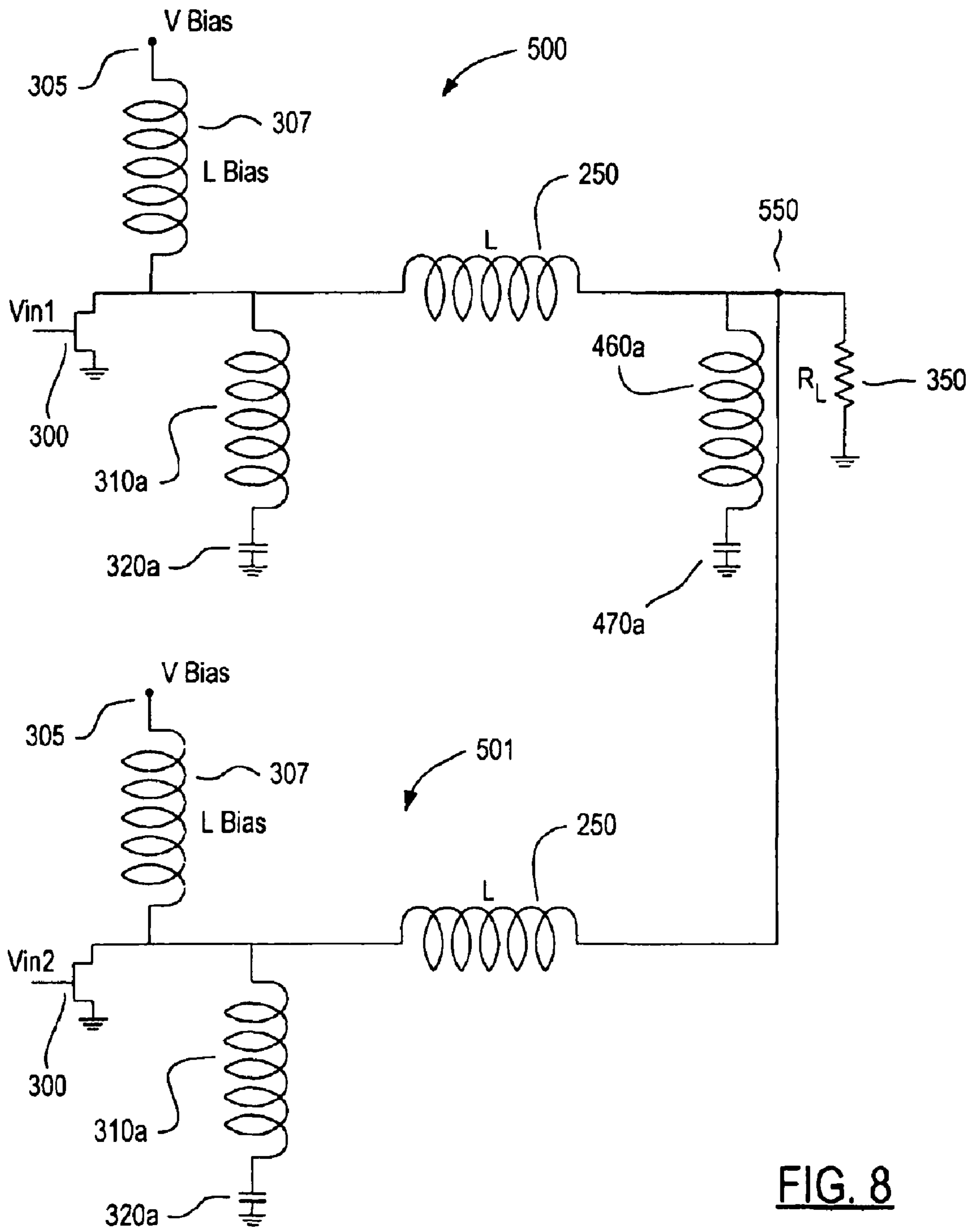


FIG. 8

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**SWITCHED-MODE POWER AMPLIFIER
USING LUMPED ELEMENT IMPEDANCE
INVERTER FOR PARALLEL COMBINING**

Matter enclosed in heavy brackets [] appears in the original patent but forms no part of this reissue specification; matter printed in italics indicates the additions made by reissue.

FIELD OF THE INVENTION

The invention relates to circuitry for radio frequency (i.e. “RF” or “wireless”) transmitters and, in particular, to a switched-mode power amplifier design and configuration for parallel connection with one or more like amplifiers for combining of the signals output therefrom.

BACKGROUND OF THE INVENTION

Typically, power combiners are used in RF transmitters to combine the output signals of parallel power amplifiers into one high power RF output signal for wireless transmission. In these known transmitter structures the signals are first amplified by the power amplifiers and then they are combined by a separate power combiner to produce a combined amplified signal for transmission. Depending upon the circuit architecture and signal format used, however, it becomes necessary to make trade-offs between reducing power losses and achieving isolation between input signals of the combiner.

The need for efficiency is a particularly important design factor for the highly integrated requirements of transceivers used for wireless local area networks (LANs) and employing modulation formats such as OFDM (Orthogonal Frequency Division Multiplex). Moreover, the assignee of this invention and application has developed signal modulation methods, using OFDM signal format, whereby information signals are deconstructed into independent component signals, these independent signals being more efficiently processed and modulated than the original information signals from which they derive, and then the independent signals are up-converted, amplified and combined prior to transmission. Use of such independent modulated signals presents additional challenges to achieving efficiency at the amplification/combination stages of the transmitter, however, because the conventional model of amplification followed by combining, using known power amplifiers and combiners, is subject to inherent loss and isolation limitations.

The Chireix-type power amplifier, known to persons skilled in the art, represents one of the LINC (Linear amplification with Nonlinear Components) architectures and uses linear, saturated, or switch-mode amplifiers to provide amplification for signals having amplitude as well as phase modulation. It operates by adjusting the phase applied to two amplifiers, and combining the outputs through a combiner to reintroduce the amplitude modulation. An appropriate combiner for the Chireix architecture not only reinserts the amplitude modulation to the signal, it also provides a dynamic adjustment of the load impedance presented to each amplifier (out-phasing). This out-phasing adjustment of the load impedances is such that the DC current through each active device decreases as the combined output amplitude decreases, thereby maintaining high efficiency.

Appropriate combiners for a Chireix-type amplifier do not provide any isolation between the outputs of the two amplifiers. One example of this is a “pseudo” balanced magnetic transformer (i.e. having no center tap to ground connection)

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connecting the individual amplifier outputs to the two terminals, Input 1 and Input 2, of the input winding 100, as shown in the prior art illustration of FIG. 1. Here the magnetic transformer effectively combines, in series, in the output winding 200, the signals from the individual amplifiers and, for efficiency, the outputs of the individual amplifiers must be low impedance voltage sources. However, it will be understood by the skilled reader that such use of a magnetic transformer inherently introduces significant loss due to the limited Q achievable for the coils on a semiconductor substrate.

Alternatively, the amplifiers in a Chireix-type amplifier architecture can, instead, be connected in parallel if an appropriate impedance transformation is incorporated, that is, if the low impedance voltage source outputs (i.e. the individual amplifier outputs) are transformed into high output impedance current sources. With such a transformation, the high output impedance current source outputs can be connected in parallel, thereby avoiding the need for a magnetic transformer. As known by persons skilled in the art, this transformation can be achieved with a quarter-wave length transmission line, also referred to as an impedance inverter, as shown in the prior art illustration of FIG. 2, wherein the characteristic impedance (ZO) of the two quarter-wave length transmission lines is set to match the output impedance of the amplifier stage to the desired load impedance.

Instead of using such a quarter-wave length transmission line, the impedance inversion (transformation) can also be achieved using a lumped element equivalent circuit, as known to persons skilled in the art. Such a lumped element equivalent for broadband may consist of a series inductor, L, and two shunt negative inductances of equal absolute value, $-L$, as shown by the prior art illustration of FIG. 3A. Here, a load impedance Z_L is transformed into an input impedance $Z_{in} = \omega^2 L^2 / Z_L$. Alternatively, the lumped element equivalent circuit shown by the prior art illustration of FIG. 3B could be used for such impedance transformation. As will be appreciated by the skilled reader, these negative inductances, $-L$, can be realized, for a limited bandwidth (spot frequency) application, with the use of shunt capacitances; however, this is not applicable for a practical Class F amplifier for which such impedance inversion is needed at each of the first, second and third harmonics. Consequently, the realization of such a transformation for Class F amplifier circuits presents an obstacle for the practical design and implementation of such a circuit.

As illustrated by FIG. 4, the known switched-mode Class F amplifier provides a good approximation to a voltage square-wave across the output terminals of an active device 300 (the active device being a transistor in the usual case connected at its source, through a bias inductor 307, to a voltage rail 305) by “shorting” all even-harmonic voltages and “supporting” all odd-harmonic voltages. As a result, the voltage waveform across the output terminals of the active device 300 contains only odd-harmonic components. In addition, this sorting of odd- and even-harmonics results in a current passing through the output terminals of the active device 300 that contains the fundamental, and only even-harmonic components. Such “shorting” and “supporting” of the even and odd harmonics, respectively, is conveniently achieved, up to the third harmonic, with a series resonant circuit 310, 320 tuned to the second harmonic connected across the active device’s output terminals, and a parallel resonant circuit 330 and 340 at the third harmonic connected between the output terminal of the active device 300 and the load 350. In operation, the series resonator 310, 320 effectively shorts the second harmonic of the input signal (V_{in}) and supports the third harmonic of the input signal, while the parallel resonator 330, 340 effectively

blocks the third harmonic of the input signal from the load **350**. Since each such harmonic component contains only a voltage component or a current component, the active device **300** does not absorb power other than at the fundamental frequency. Accordingly, as a result of the second and third harmonic resonators, only (approximately) the fundamental frequency signal reaches the load **350** at output terminal **351**.

From a practical perspective, it is known that using such resonator circuits to process the input signal only up to its third harmonic components can provide a power-added efficiency of up to about 90%. However, it is also known that this Class F amplifier circuit architecture, where used at high frequencies, presents a design problem relating to the resonator circuits in that a source-drain (emitter-collector) parasitic capacitance results across the active device and causes the resonance values of these resonators to detune. In turn, this means that some level of amplitude for all harmonics of the voltage and current will exist, in practice, at such high frequencies.

By reason of the foregoing limitations, for a Class F, Chireix-type amplifier architecture there exists a need for new and efficient means to achieve power amplification and combining of modulated signals in transmitters.

SUMMARY OF THE INVENTION

In accordance with the invention, there is provided a switched-mode Class F power amplifier configured for parallel connection with at least one other like amplifier for combining signals output from such parallel connected amplifiers. An input component comprises at least one active device configured to be alternately switched by a signal (i.e. an analog phase modulated signal) input thereto to present an amplified signal corresponding to the input signal, the amplified signal constituting a low output impedance voltage source. A lumped element impedance inverter is provided between the input component and an output resonator component, the impedance inverter being configured for transforming the low output impedance voltage source so as to constitute a high output impedance current source configured for the parallel connection. Negative reactive component values required by the impedance inverter are eliminated and effectively provided by incorporating those negative values into pre-selected reactive components of the input and output components.

Optionally, a source-drain parasitic capacitance across the active device is also eliminated by one or more pre-selected reactive components of the input component, with the value(s) of the pre-selected reactive components being predetermined to effectively compensate for the parasitic capacitance.

In accordance with another aspect of the invention a plurality of the foregoing amplifiers are connected in parallel for combining signals output from the amplifiers wherein an input component is provided for each of the plurality of amplifiers. A common output resonator component is provided (common to all of the plurality of amplifiers) and a lumped element impedance inverter for each of the plurality of amplifiers between the input component and output component. As for the single amplifier, the negative reactive component values required by each impedance inverter is eliminated and effectively provided by incorporating their values into pre-selected reactive components of the input and output components.

In accordance with a further aspect of the invention there is provided a method for amplifying an input signal to produce an output signal configured for parallel connection with at

least one other like output signal for combining the output signals within a Chireix circuit architecture. The input signal is amplified by means of at least one active device configured to be alternately switched by the input signal and an amplified signal corresponding to the input signal is presented, the amplified signal constituting a low output impedance voltage source. A second harmonic resonator configured for shorting a second harmonic signal of said input signal is provided across the active device. The low output impedance voltage source is transformed to constitute a high output impedance current source by means of a lumped element impedance inverter, the high output impedance current source being configured for the parallel connection. A third harmonic resonator blocks a third harmonic signal of the input signal from a load connected to the output signal. Negative reactive component values required by the impedance inverter are eliminated and effectively provided by incorporating those negative values into preselected adjacent reactive components of the resonators.

BRIEF DESCRIPTION OF THE DRAWINGS

An exemplary preferred embodiment of the invention is described in detail below with reference to the following drawings in which like references refer to like elements throughout:

FIG. 1 illustrates a prior art pseudo balanced, transformer (i.e. not having a centre-tap-to-ground connection) for series-combining the output signals (Input 1 and Input 2) of a switched-mode power amplifier;

FIG. 2 illustrates a quarter-wavelength ($\lambda/4$) transmission line (impedance inverter), useful for transforming a high output impedance to a low output impedance, as known by persons skilled in the art;

FIGS. 3A and 3B illustrate two different, alternate lumped element circuit equivalents to the foregoing quarter-wavelength transmission line of FIG. 2;

FIG. 4 illustrates a conventional Class F switched-mode power amplifier circuit;

FIG. 5 illustrates a Class F switched-mode power amplifier circuit according to that of FIG. 4 but with the addition of an impedance inverter, per that of FIG. 3A, connected to the output terminal of the amplifier before the load;

FIG. 6 illustrates a modified Class F amplifier circuit over that of FIG. 5, which includes the impedance inverter (transformer) of FIG. 5 but replaces the parallel third-harmonic-tuned resonator circuit of FIG. 5, with a series third-harmonic-tuned resonator circuit connected across the output terminal of the amplifier to ground;

FIG. 7 illustrates a further modified Class F amplifier over that of FIG. 6, in accordance with the present invention, in parallel connection with a like amplifier according to the invention, wherein the left-most negative inductor ($-L$) of the impedance inverter (transformer) of FIG. 6 is incorporated into the series second-harmonic-tuned resonator circuit of FIG. 6 to produce the modified series second-harmonic-tuned resonator circuit shown in this figure and the rightmost negative inductor ($-L$) of the impedance inverter (transformer) of FIG. 6 is incorporated into the series third-harmonic-tuned resonator circuit of FIG. 6 to produce the modified series third-harmonic-tuned resonator circuit shown in this figure; and,

FIG. 8 illustrates modified parallel-connected circuit of Class F amplifiers configured in accordance with the invention, over that of FIG. 7, in which the output third harmonic

resonator components are replaced by one equivalent output resonator component common to both amplifiers.

DETAILED DESCRIPTION OF THE ILLUSTRATED EMBODIMENT

Surprisingly, the inventor has invented a Class F amplifier configured for parallel connection with at least one other like amplifier, for combining the outputs of such parallel connected amplifiers in a Chireix circuit architecture, which overcomes or avoids the disadvantages associated with the foregoing prior art transformer couplings used for combining amplifier outputs and impedance inverters in the form of quarter-wavelength transmission lines or lumped element equivalents thereto having negative reactive components.

As illustrated by FIG. 5, the present invention is achieved by first transforming, by means of an impedance inverter **335** (consisting of series positive inductor **250** and shunt negative inductors **260, 270**), the output of a Class F amplifier (i.e. at terminal **333**) from that of a low impedance voltage source to a high impedance current source so that such output-transformed amplifier may be connected in parallel with another like amplifier configuration to combine the outputs of the two amplifiers. Then, as illustrated by FIG. 6, the parallel third harmonic resonator **330, 340** is transformed through that impedance inverter **335** into a series third harmonic resonator **360, 370** (i.e. the parallel resonator **330, 340** is replaced by a series resonator **360, 370** across the output terminal **351** and ground). Then, as illustrated by FIG. 7 (which shows two such amplifier circuits **500, 501**, each configured in accordance with the present invention and connected in parallel to present an output signal at terminal **550** representing an amplification and-combination of input signals V_{in1} and V_{in2}) the negative impedances **260, 270** are eliminated by incorporating those negative impedance values (effects) into the values of pre-selected existing reactive components adjacent to them.

Specifically, as shown by FIG. 7, the negative impedance **260** is incorporated into the series second harmonic resonator **310, 320** to form a modified series second harmonic resonator **310a, 320a** in the example shown. Alternatively, if the source bias voltage **305** is stable, that negative impedance could be incorporated into the source bias inductor **307**. Also as illustrated by FIG. 7, the negative impedance **270** is incorporated into the series third harmonic resonator **360, 370** in the example shown to form a modified series third harmonic resonator **360a, 370a**.

Further, since this modified third harmonic resonator circuit **360a, 370a** of the amplifier **500** is in parallel connection with the corresponding resonator circuit **360a, 370a** of the parallel-connected like amplifier **501**, these resonator circuits may be replaced by one equivalent resonator circuit **460a, 470a**, as shown by FIG. 8.

Moreover, the inventor has also advantageously eliminated the aforementioned source-drain parasitic capacitance of the Class F amplifier which occurs at high frequencies, by compensating for its presence in the pre-selection of the modified values of the components **310a, 320a** of the second harmonic resonator.

It has also been determined by the assignee of this invention that the positive inductance **250** of the impedance inverter can be realized as a wire-bond in a semiconductor product implementation of this circuit, whereby the actual Chireix (parallel) signal combining takes place off die at the package pin. The means and method of performing such a wire-bond realization is described in detail in a co-pending application assigned to the same assignee as this application,

entitled "Integrated Circuit Incorporating Wire Bond Inductance" which was filed on 30 Jun., 2003.

The individual electronic and processing functions utilised in the foregoing described embodiment are, individually, well understood by those skilled in the art. Appropriate values to be pre-selected for the surrounding reactive components, for given signal frequencies, to incorporate the negative reactive values of the impedance inverter in accordance with the invention, can be readily determined, as needed, by such skilled persons. It is to be understood by the skilled reader that a variety of other implementations of the invention, apart from the specific embodiment illustrated herein, may be devised for substitution. The claimed invention herein is intended to encompass all such alternative implementations, substitutions and equivalents. Persons skilled in the field of electronic and communication design will be readily able to apply the present invention to an appropriate implementation for a given application.

Consequently, it is to be understood that the particular embodiments shown and described herein by way of illustration are not intended to limit the scope of the invention claimed by the inventors/assignee which is defined by the appended claims.

What is claimed is:

1. A switched-mode Class F power amplifier configured for parallel connection with at least one other said amplifier for combining signals output from such parallel connected amplifiers, said amplifier comprising:

- (a) an input component comprising at least one active device configured to be alternately switched by a signal input thereto to present an amplified signal corresponding to said input signal, said amplified signal constituting a low output impedance voltage source;
- (b) an output resonator component; and
- (c) a lumped element impedance inverter connected between said input component and said output component, said impedance inverter configured for transforming said low output impedance voltage source so as to constitute a high output impedance current source, and said high output impedance current source configured for said parallel connection;

wherein negative reactive component values theoretically required by said impedance inverter are actually incorporated into pre-selected reactive components of said input and output components.

2. A switched-mode power amplifier according to claim 1 wherein said input signal is an analog phase modulated signal.

3. A method for producing a switched-mode power amplifier, said method comprising:

- (a) designing a theoretical lumped-element impedance inverter configured to transform a low output impedance voltage source into a high output impedance current source, such ideal impedance inverter incorporating theoretically negative reactive component values;
- (b) adding an input component comprising at least one active device configured to be alternately switched by an input signal thereto to present an amplified signal corresponding to said input signal, said amplified signal constituting a low output impedance voltage source;
- (c) adding an output resonator component; and
- (d) adjusting values of one or more elements coupled to the input and output components such that the theoretically negative reactive components may be eliminated, and eliminating the theoretically negative reactive components from the design.

4. A method according to claim 3 whereby said input signal is an analog phase modulated signal.

5. A plurality of switched-mode Class F power amplifiers in parallel connection for combining signals output from said amplifiers, said parallel-connected amplifiers comprising:

(a) an input component for each of said plurality of amplifiers, each said input component comprising at least one active device configured to be alternately switched by a signal input thereto to present an amplified signal corresponding to said input signal, said amplified signal constituting a low output impedance voltage source;

(b) a common output resonator component for said plurality of amplifiers; and

(c) a lumped element impedance inverter for each of said plurality of amplifiers between said input component and said output component, said impedance inverter configured for transforming said low output impedance voltage source so as to constitute a high output impedance current source and said high output impedance current source configured for said parallel connection; wherein negative reactive component values required by said impedance inverter are eliminated and effectively provided by incorporating said values into pre-selected reactive components of said input and output components.

6. The switched-mode power amplifier according to claim 1, wherein the input component comprises a first inductor and a first capacitor, connected in series and electrically connected to the input of the impedance inverter.

7. The switched-mode power amplifier according to claim 6, wherein the output component comprises a second inductor and a second capacitor, connected in series and electrically connected to the output of the impedance inverter.

8. The switched-mode power amplifier according to claim 7, wherein the values for each of the first inductor, first capacitor, second inductor and second capacitor are selected in order to compensate for the negative reactive component values theoretically required but not otherwise included in the amplifier.

9. The method of claim 3, further comprising manufacturing the switched-mode power amplifier.

10. The method of claim 9, wherein the input component comprises a first inductor and a first capacitor, connected in series and electrically connected to the input of the impedance inverter.

11. The method of claim 10, wherein the output component comprises a second inductor and a second capacitor, connected in series and electrically connected to the output of the impedance inverter.

12. The method of claim 11, further comprising the step of selecting the values for each of the first inductor, first capacitor, second inductor and second capacitor in order to compensate for the negative reactive component values theoretically required but not present in the manufactured amplifier.

13. *An apparatus, comprising:*
means for amplifying an input signal to generate a low output impedance voltage source by alternately switching an input component, wherein the input component includes at least one active device responsive to the input signal; and

means for transforming the low output impedance voltage source into a high output impedance current source using a lumped-element impedance inverter coupled to the means for amplifying;

wherein negative reactive component values theoretically required by the lumped-element impedance inverter include pre-selected reactive components; and

wherein the means for amplifying includes a first inductor means serially connected to a first capacitor means and electrically connected to an input of the lumped-element impedance inverter.

14. *The apparatus of claim 13, further comprising:*
output resonator means coupled to both the means for amplifying and the means for transforming;
wherein the output resonator means includes a second inductor means serially connected to a second capacitor means and electrically connected to an output of the lumped-element impedance inverter.

15. *The apparatus of claim 14, further comprising means for selecting the values for each of the first inductor means, the first capacitor means, the second inductor means, and the second capacitor means to compensate for the negative reactive component values theoretically required but not present in the apparatus.*

16. *An apparatus, comprising:*
means for amplifying an input signal;
means for resonating a resonant frequency, wherein the means for resonating is coupled to the means for amplifying; and
means for inverting an impedance, wherein the means for inverting is coupled between the means for amplifying and the means for resonating;

wherein the means for inverting includes means for transforming an output of the means for amplifying from a voltage source having a low output impedance into a current source having a high output impedance; and wherein the means for inverting further includes one or more negative valued theoretical reactive components realized as one or more positive valued reactive components of at least one of the means for amplifying or the means for resonating, or a combination thereof.

17. *The apparatus of claim 16, wherein the means for resonating comprises means for realizing an inductance serially connected to a means for realizing a capacitance, and wherein at least one of the means for realizing an inductance or the means for realizing a capacitance, or a combination thereof, incorporates a negative reactive component of the means for inverting.*

18. *An amplifier, comprising:*
an input component including at least one active device configured to be alternately switched by an input signal to generate a low output impedance voltage source; and an impedance converter coupled between the input component and an output component and configured to generate a high output impedance current source in response to the low output impedance voltage source; wherein the input component and the output component both include reactive components that eliminate negative reactive component values theoretically required by the impedance converter.

19. *The amplifier of claim 18, wherein the input signal comprises an analog phase-modulated signal.*

20. *The amplifier of claim 18, wherein the input component comprises a first inductor serially connected to a first capacitor.*

21. *The amplifier of claim 20, wherein the output component comprises a second inductor serially connected to a second capacitor.*

22. *The amplifier of claim 21, wherein the first inductor, the first capacitor, the second inductor, and the second capacitor are selected to compensate for the negative reactive component values theoretically required but not present in the amplifier.*

UNITED STATES PATENT AND TRADEMARK OFFICE
CERTIFICATE OF CORRECTION

PATENT NO. : RE42,612 E
APPLICATION NO. : 11/787231
DATED : August 16, 2011
INVENTOR(S) : Grundlingh

Page 1 of 1

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

Title page, item (12), under "Reissued Patent", in Column 1, Line 1, delete "Grundlingh" and insert -- Grundlingh --.

Title page, item (75), under "Inventor", in Column 1, Line 1, delete "Grundlingh," and insert -- Grundlingh, --.

Signed and Sealed this
Tenth Day of January, 2012

A handwritten signature in black ink that reads "David J. Kappos". The signature is written in a cursive style with a large initial 'D' and 'K'.

David J. Kappos
Director of the United States Patent and Trademark Office