A cross-differential amplifier is provided. The cross-differential amplifier includes an inductor connected to a direct current power source at a first terminal. A first and second switch, such as transistors, are connected to the inductor at a second terminal. A first and second amplifier are connected at their supply terminals to the first and second switch. The first and second switches are operated to commutate the inductor between the amplifiers so as to provide an amplified signal while limiting the ripple voltage on the inductor and thus limiting the maximum voltage imposed across the amplifiers and switches.
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FIGURE 1

load network

FIGURE 2

$V_{\text{switch}}$

equal areas

$V_{\text{Supply}}$

time
FIGURE 3

FIGURE 4

The U.S. Government has certain rights to this invention pursuant to Grant No. DAAG55-97-1-0254 awarded by the Army and Grant No. NPO 30176 awarded by NASA.

FIELD OF THE INVENTION

The present invention pertains to the field of amplifiers. More specifically, the invention relates to a cross-differential amplifier that can operate at higher supply voltages.

BACKGROUND OF THE INVENTION

High efficiency saturated amplifiers and switching power amplifiers are known in the art. One drawback with the use of such amplifiers is the high peak voltages relative to the dc supply that the active devices must withstand in these modes of operation. In order to improve the gain, switching speed, and on-resistance of transistors, the breakdown voltage of the device is usually reduced. This tradeoff is exhibited by all modern semiconductor device technologies, including but not limited to field-effect transistors (FET), bipolar junction transistors (BJT), heterojunction bipolar transistors (HBT), high electron mobility transistors (HEMT), metal-semiconductor field-effect transistors (MESFET), metal-oxide semiconductor field-effect transistors (MOSFET), and junction field-effect transistors (JFET). The effect is also independent of the semiconductor material system from which the devices are constructed, including but not limited to gallium arsenide (GaAs), indium phosphide (InP), silicon-germanium (SiGe), and silicon (Si) processes such as silicon bipolar (Si BJT), complementary metal oxide field effect transistor (CMOS) processes, and silicon-on-insulator (SOI) technologies.

In high efficiency switching amplifiers, such a reduction in breakdown voltage can be problematic. Unlike many applications in which the maximum voltage seen by any device is typically limited to the dc voltage of the power source, high efficiency switching amplifiers such as class E, class F, class inverse-F, current-mode class D and class E/F can require that the peak voltage seen by the devices be several times the dc supply. Class F, for instance, can require a peak voltage at least twice the supply voltage, whereas class E can require the device to withstand over 3.5 times the supply voltage without breaking down.

This high peak voltage relative to the dc power supply voltage applied results from the use of an inductor to connect the active device to the dc supply voltage. FIG. 1 is a diagram of a generalized circuit topology typically used in saturated and switching amplifiers such as class E, class F, and class E/F. The active device is connected to the dc supply through the inductor. Since the dc (or average) voltage drop across any inductor at steady state can be zero, the voltage waveform can have an average voltage equal to the supply voltage. This corresponds to a limitation on the waveform that the average area above the supply voltage and the area below it must be the same. This can be seen in FIG. 2, depicting typical waveforms for a representative switching amplifier, with equal areas above and below the supply voltage shaded.

As can be seen in FIG. 2, the active device spends a significant portion of its time in a low voltage state. This is so that the active device can conduct the bulk of its current during this time, thereby reducing the power dissipation in the device, resulting in high efficiency. Unfortunately, this results in a very large area below the supply voltage, necessitating an equally large area above it. Thus the voltage during the times when the switch is not low can be significantly greater than the supply voltage, usually by a factor of two to four.

In a typical CMOS process, for instance, the device breakdown can be less than 6V whereas the supply voltage is in many cases 3.3 V or higher. With a 3.3 V supply, the class E amplifier can produce waveforms with peak voltage greater than 11 V, almost twice that which a CMOS device with 6 V breakdown can tolerate. Thus in this application, the supply voltage can be changed, a more expensive high-voltage process can be used, or a less efficient type of power amplifier with a lower peak voltage can be employed. If the supply voltage cannot be changed, such as if it is coming from a battery or if other circuits on the same supply cannot change their supply voltage, the high peak to supply ratio of the traditional switching amplifiers thus forces a sacrifice in either cost or performance.

SUMMARY OF THE INVENTION

In accordance with the present invention, a cross-differential amplifier is provided that overcomes known problems with existing amplifiers.

In particular, a cross-differential amplifier is provided that allows devices with low breakdown voltage such as high-frequency transistors or integrated circuit transistors to be used with higher supply voltages.

In accordance with an exemplary embodiment of the present invention, a cross-differential amplifier is provided. The cross-differential amplifier includes an inductor connected to a dc power source at a first terminal. A first and second switching device, such as transistors, are connected to the inductor at a second terminal. A first and second amplifier are connected to the first and second switching devices at their supply points. The first and second switch are configured to connect the two amplifiers to the inductor in an alternating fashion so that each amplifier receives current and that the average voltage on the second terminal of the inductor is greater than the average voltage of one of the amplifiers at its supply point.

The present invention provides many important technical advantages. One important technical advantage of the present invention is an amplifier that can be used in high efficiency switching modes, such as in classes E, inverse F, E/F, current-mode class D, and other suitable classes, while operating from higher supply voltages while using lower breakdown voltage devices.

Those skilled in the art will appreciate the advantages and superior features of the invention together with other important aspects thereof on reading the detailed description that follows in conjunction with the drawings.
with an exemplary embodiment of the present invention; present invention. By using more than two amplifiers, each
plary embodiment of the present invention; even further reduce the peak voltages on the amplifying
sections relative to one another so that their peak voltages occur at or other suitable switches or three terminal devices having a
three amplifying sections 

amplifier waveforms, showing the equal areas above and below the supply voltage due to the inductive supply con-
nection; cycle of each amplifying section is nearly zero, the cross
amplifying sections

In the description that follows like parts are marked throughout the specification and drawings with the same reference numerals, respectively. The drawing figures are not necessarily to scale and certain features can be shown in somewhat generalized or schematic form in the interest of clarity and conciseness.

FIG. 3 is a diagram of a typical saturated or switching amplifier using an inductor for the supply connection;

FIG. 2 is a diagram of typical saturated or switching amplifier waveforms, showing the equal areas above and below the supply voltage due to the inductive supply connection;

FIG. 3 is a diagram of a cross differential amplifier in accordance with an exemplary embodiment of the present invention;

FIG. 4 is a diagram of voltage waveforms in accordance with an exemplary embodiment of the present invention;

FIG. 5 is a diagram of a cross differential amplifier with three conmutated amplifiers in accordance with an exemplary embodiment of the present invention;

FIG. 6 is a diagram of a cross differential amplifier with several two terminal switches used to implement the n-way commutation switch in accordance with an exemplary embodiment of the invention;

FIGS. 7A through 7C are diagrams of cross differential amplifiers in accordance with exemplary embodiments of the present invention;

FIG. 8 is a diagram of a cross differential amplifier which can be operated in class E mode in accordance with an exemplary embodiment of the present invention;

FIG. 9 is a diagram of a cross differential amplifier which can be operated in class inverse F, current-mode class D, or class E/F, modes in accordance with an exemplary embodiment of the present invention;

FIG. 10 is a diagram of a cross differential amplifier with intrinsic capacitances and which can be operated in class inverse F, current-mode class D, or class E/F, modes in accordance with an exemplary embodiment of the present invention;

FIG. 11 is a diagram of a distributed active transformer in accordance with an exemplary embodiment of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

In one exemplary implementation, the two amplifying sections 302 and 304 are driven with different phases
LDMOS transistors, HEMT transistors, MESFET transistors

and device 708 can also be operated so that device 704 and device 708 are used as the commutating
switches while using device 702 and device 706 as the amplifying devices. In this mode, device 704 and device 708 alternately force device 702 and device 706 to support the voltage at the second terminal of inductor 710, allowing a reduction of peak voltage on device 702 and device 706 for the same dc supply voltage.

Cross differential amplifier 700A can also be used so that all four devices are switching, so that each pair of switching amplification devices acts as a commutator for the other, or in other suitable manners.

FIG. 7C is a diagram of a cross differential amplifier 700C where inductor 710 has been placed at the ground side of the circuit and the supply voltage is connected directly to device 702 and device 706. Cross differential amplifier 700C can behave substantially like cross differential amplifier 700A in regards to its behavior. In cross differential amplifier 700C, device 704 and device 708 can be used as switches to connect device 702 and device 706 between supply 712 and inductor 710, resulting in the same peak voltage reduction effect on device 702 and device 706. In this case, the inductor is connected to ground, so that the effect is achieved by connecting devices 702 and 706 to the inductor 710 in such a way as to reduce the time that the inductor sees voltages significantly higher than ground. For instance, in one exemplary embodiment, devices 704 and 708 can be operated to commutate inductor 710 between devices 702 and 706 so as to keep the inductor connected throughout the cycle to the amplifying device which has the most negative voltage at its output terminal.

Cross differential amplifier 700C can also be operated so that device 702 and device 706 are used as commutating switches, while using devices 704 and 708 as amplifying devices. In this mode, devices 702 and 706 alternately force the amplifying devices to support the voltage difference between the power supply voltage and the commutating point of inductor 710, allowing a reduction of the peak voltage on devices 704 and 708.

Cross differential amplifier 700C can also be used so that all four devices are switching so that each pair of amplifying switches commutates the current for the other, or in other suitable manners.

FIG. 7D is a diagram of cross differential amplifier 700D in accordance with an exemplary embodiment of the present invention. Cross differential amplifier 700D includes inductor 710A connected to device 702 and device 706, and inductor 710B connected to device 704 and device 708. Since these inductors are connected in series with each other and with the dc power supply 712, this implementation also operates substantially the same as cross differential amplifier 700A. By using devices 702 and 706 as switches to commutate inductors 710A and 710B between devices 704 and 708, which are used as amplifying devices, the voltage ripple on inductors 710A and 710B can be reduced, which also reduces the peak voltage seen on device 702 and 706 and devices 704 and 708 for a given dc supply voltage.

Cross differential amplifier 700B can also be used so that device 704 and device 708 are used as commutating switches, while using devices 702 and 706 as amplifying devices. In this mode, devices 704 and 708 alternately force the amplifying devices to support the voltage difference between the supply inductors 710A and 710B, allowing a reduction of the peak voltage on devices 702 and 706.

Cross differential amplifier 700B can also be used so that all four devices are switching so that each pair of amplifying switches commutates the current for the other, or in other suitable manners.

In operation, the load network and bias points for the amplifiers of cross differential amplifiers 700A, 700B and 700C can be selected so as to allow operation in class E, class A/B, class B, class C, class E, inverse F, and class E/F (signifying any class of switching amplifier operation belonging to the family of switching amplifiers E/F). An example of class E/F amplifiers is provided by U.S. application Ser. No. 60/974,557, “Class E/F Switching Power Amplifiers,” filed Oct. 9, 2001, and which is hereby incorporated by reference for all purposes. Cross differential amplifiers 700A through 700C can be used where switching amplifier tunings are used since all four devices can be made to simultaneously operate in the high efficiency class E, inverse F, current-mode class D, and class E/F modes.

FIG. 8 is a diagram of a cross differential amplifier 800 which can be operated in class-E mode in accordance with an exemplary embodiment of the present invention. Cross differential amplifier 800 includes devices 802, device 804, device 806, and device 808, which can be operated as switches, or other suitable devices. Device 802 and device 808 can be operated as a first set in opposition to the phase of device 806 and device 804, such that current is driven through inductor 836, capacitor 830, and resistor 832 in a first direction through device 802 and device 808, and then in a second direction through device 806 and device 804. Inductor 826, capacitor 830, and resistor 832 can be sized to resonate at the operating frequency, and to supply a suitable impedance at the operating frequency so as to compensate for capacitor 818, capacitor 820, capacitor 822, and capacitor 824, which can be the internal capacitances of devices 802 through 808, respectively, or other suitable capacitances, so as to allow cross differential amplifier 800 to operate in the class-E mode of operation. In one exemplary embodiment, capacitors 818 through 824 can be the intrinsic capacitance of devices 802 through 808, respectively, can be capacitances between devices 802 through 808 and external components or features, can be a suitable combination of such capacitances, or can include other suitable capacitors or capacitance. In another exemplary embodiment, resistor 832 can be a resistive load to be driven, the resistive component of a reactive load to be driven, an antenna, the input of an amplifier or other circuit, or other suitable loads or combinations of loads.

Using this technique, inductor 810 which is used for class E operation does not have a large voltage across it for long periods of time since it does not connect directly to ground as is the case in conventional class E amplifiers. In this manner, the peak voltage at the node shared by device 802, device 806, and inductor 810 is less than the peak voltage of the equivalent node of a conventional class-E switching differential amplifier such as one that uses independent inductors to connect each of the amplifying devices to the supply, or of the equivalent node of a conventional class-E switching amplifier. By selecting appropriate values for inductor 826, capacitor 830, resistor 832, and capacitors 818 through 824, each device 802 through 808 can be switched at a time when the voltage is at or close to zero, so as to minimize the turn -on switching losses due to capacitances 818 through 824 (equal to \( \frac{1}{2} CV^2 \)), and which results in undesirable power losses and heating. Cross differential amplifier 800 can also be used in the configurations shown in FIGS. 7B and 7C, with supply inductors in other suitable locations. Additionally, the load network can consist of the series RLC network depicted in FIG. 8, or other suitable single-ended or differential loads meeting the class-E tunings conditions for each amplifying device.
FIG. 9 is a diagram of a cross differential amplifier 900 which can be operated in current-mode class D, class inverse F or class E/F, modes of operation in accordance with an exemplary embodiment of the present invention. Cross differential amplifier 900 includes device 902, device 904, device 906 and device 908, each of which can be operated as switches or other suitable devices, and inductor 910 and supply voltage 912. Device 902 and device 908 operate in phase with each other and opposite to the phase of device 906 and device 904, such that in the first state of operation, current flows through inductor 910 and device 902 across a load formed by capacitor 918, resistor 920, and inductor 922, and through device 908. Likewise, in the second state of operation, current flows through inductor 910 and device 906 through the load formed by capacitor 918, resistor 920, and inductor 922 connected in parallel, and through device 904. Inductor 922, capacitor 918, and resistor 920 are selected to provide suitable tuning for current-mode class D, class inverse F or class E/F modes of operation. In one exemplary embodiment, resistor 920 can be a resistive load to be driven, the resistive component of a reactive load to be driven, an antenna, the input of an amplifier or other circuit, or other suitable loads or combinations of loads.

Using this technique, the supply inductor 910 which can be used for current-mode class D, inverse-F and E/F modes of operation can avoid having large voltage across it for periods of time since it is not connected directly to ground for large portions of the cycle as is the case in conventional current-mode class D, inverse-F and E/F amplifiers. This configuration allows the peak voltage of the node shared by the inductor 910 and devices 902 and 906 to be less than the peak voltage of the equivalent node of a conventional switching differential amplifier using two inductors to connect the two devices to the voltage source, each one individually, or, the equivalent node of a conventional class inverse F, current-mode class D, or class E/F switching amplifier. Cross differential amplifier 900 can also be used in the configurations shown in FIGS. 7B and 7C, with supply inductors in other suitable locations. Additionally, the load network used can be a suitable single-ended or differential network which results in E/F operation.

FIG. 11 is a diagram of a distributed active transformer 1100, in accordance with an exemplary embodiment of the present invention. Distributed active transformer 1100 includes cross differential amplifiers 1102, 1104, 1106 and 1108, which are connected to provide primary winding segments 1110, 1112, 1114, and 1116. Secondary winding 1118 includes output 1120, and is magnetically connected to the primary winding sections 1110 through 1116. The current through each primary winding section is controlled by the corresponding cross differential amplifier, such that a distributed transformer architecture is provided that uses cross differential amplifiers as primary winding sections. Although four cross differential amplifiers are shown in this implementation, any suitable number of amplifying devices can be combined in the distributed active transformer. The various cross differential amplifiers can also be used in the configurations shown in FIGS. 7B and 7C, with inductors in other suitable locations.

Although exemplary embodiments of the system and method of the present invention has been described in detail herein, those skilled in the art will also recognize that various substitutions and modifications can be made to the system and methods without departing from the scope and spirit of the appended claims.

What is claimed is:
1. A device utilizing a cross-differential amplifier comprising:
a switchable mode where the current can be controlled:

- an inductor connected to a power source at a first terminal;
- a switch for reducing a voltage ripple on the inductor; and
- a plurality of amplifiers connected to the switch.

2. The device of claim 1 further comprising a class inverse F load coupled to an output of the cross-differential amplifier.

3. The device of claim 1 comprising a class D load coupled to an output of the cross-differential amplifier.

4. The device of claim 1 comprising a class E/F load coupled to an output of the cross-differential amplifier.

5. The device of claim 1 comprising a class E/F load coupled to an output of the cross-differential amplifier.

6. The device of claim 1 comprising a class E/F load coupled to an output of the cross-differential amplifier.

7. The device of claim 1 comprising a class E/F load coupled to an output of the cross-differential amplifier.

8. The device of claim 1 comprising a switch for reducing a voltage ripple on the inductor at a radio frequency.
9. A system utilizing a cross-differential amplifier comprising:
   a first active device connected to the inductor for reducing
   the voltage ripple on the inductor; and
   a second active device means for amplifying a signal, the
   second active device means connected to the first active device to form an output.

10. The system of claim 9 wherein the second active device means is operated as a controlled current source.

11. The system of claim 9 wherein the second active device means amplifies the signal at a radio frequency.

12. The system of claim 9 comprising a class E load coupled to the output.

13. The system of claim 9 comprising a class E constant load coupled to the output.

14. The system of claim 9 comprising a class E/F load coupled to the output.

15. A method for operating a cross-differential amplifier comprising:
   step means for operating a first switch and a second switch
   to reduce a voltage ripple on an inductor; and
   step means for forming a first current path containing a
   power source and a second current path containing the
   power source.

16. The method of claim 15 comprising step means for operating the cross differential amplifier at a radio frequency of operation.

17. The method of claim 15 comprising step means for operating the first and second switches at a radio frequency of operation.

18. The method of claim 15 comprising step means for operating the first, second, third, and fourth switches at a radio frequency of operation.

19. The method of claim 15 comprising step means for operating the first, second, third, and fourth switches at a radio frequency of operation.