

# UK Patent Application GB 2636498

(43) Date of A Publication

(13) A  
18.06.2025

(21) Application No: 2418671.0  
(22) Date of Filing: 10.08.2021  
Date Lodged: 19.12.2024  
(30) Priority Data:  
(31) 63065051 (32) 13.08.2020 (33) US  
(31) 63146093 (32) 05.02.2021 (33) US  
(31) 17314890 (32) 07.05.2021 (33) US  
(31) 17314917 (32) 07.05.2021 (33) US  
(31) 17343479 (32) 09.06.2021 (33) US  
(31) 17349536 (32) 16.06.2021 (33) US  
(31) 2109569 (32) 02.07.2021 (33) GB

(62) Divided from Application No  
2300338.7 under section 15(9) of the Patents Act 1977

(71) Applicant(s):  
Cirrus Logic International Semiconductor Limited  
7B Nightingale Way, Quartermile, Edinburgh,  
EH3 9EG, United Kingdom

(72) Inventor(s):  
Axel Thomsen  
Eric King  
Anthony Doy  
Thomas Hoff  
John Melanson

(74) Agent and/or Address for Service:  
Haseltine Lake Kempner LLP  
One Portwall Square, Portwall Lane, BRISTOL,  
BS1 6BH, United Kingdom

(54) Title of the Invention: **Driver circuitry and operation**  
Abstract Title: **Multimode driver circuitry and operation**

(57) A driver circuit 1200 has a first switching driver 401-1 and a second switching driver 401-2 for driving a transducer 104 in a bridge-tied-load (BTL) configuration, each switching driver having a respective output stage for controllably switching a respective driver output node between high and low switching voltages with a controlled duty cycle. Each switching driver is operable in a plurality of different driver modes, wherein the switching voltages are different in said different driver modes (e.g. Table 1). A controller 1201 controls the driver mode of operation and the duty cycle of the switching drivers based on the input signal. The controller is configured to control the duty cycles of the first and second switching drivers within defined minimum and maximum limits of duty cycles, and to transition between driver modes of operation when the duty cycle of one of the switching drivers reaches a duty cycle limit (Fig.13, 1301, 1302). The controller implements the transition by changing the driver mode of one switching driver and varying its duty cycle to the other duty cycle limit, and by maintaining the driver mode of the other switching driver and varying its duty cycle to maintain the differential output signal magnitude.

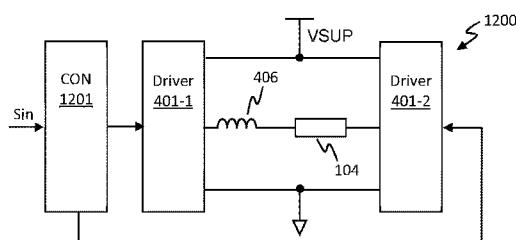


Figure 12

GB 2636498 A

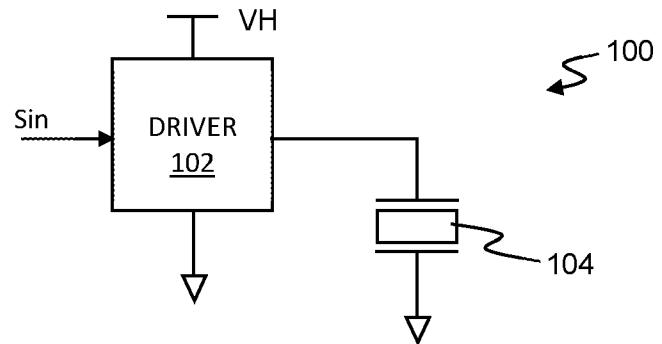


Figure 1

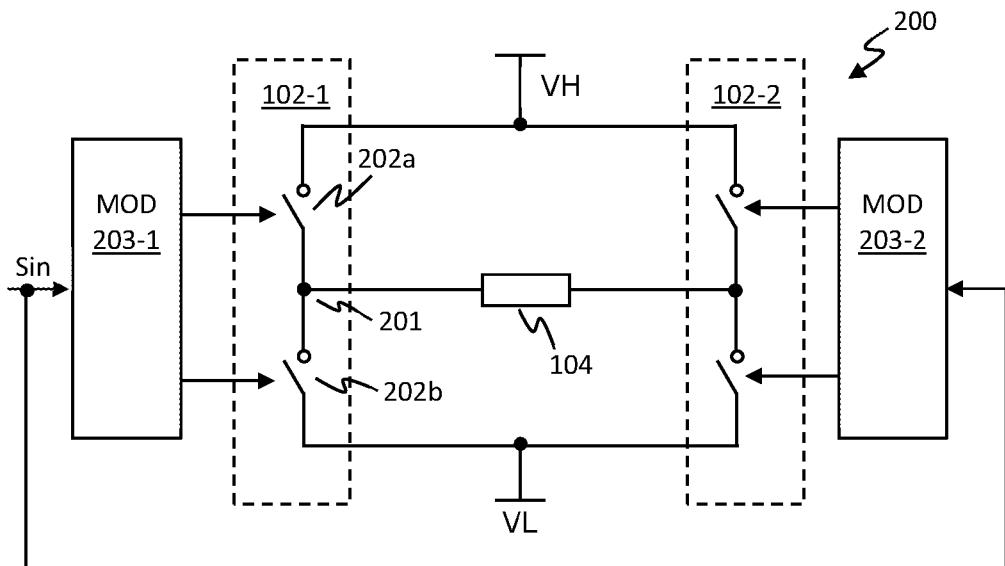


Figure 2

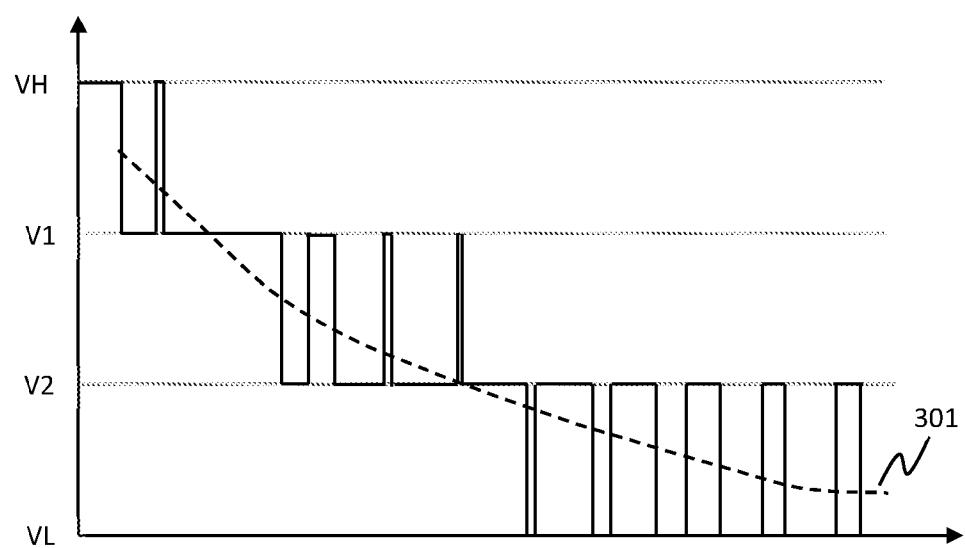


Figure 3

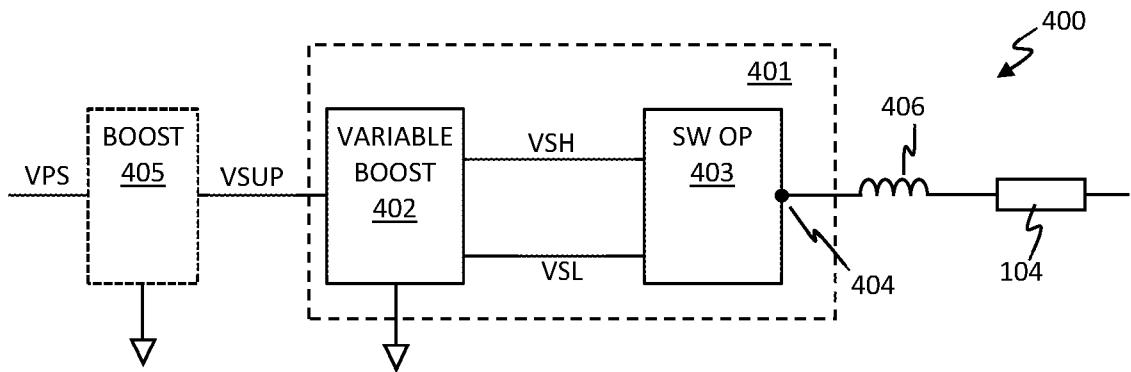


Figure 4

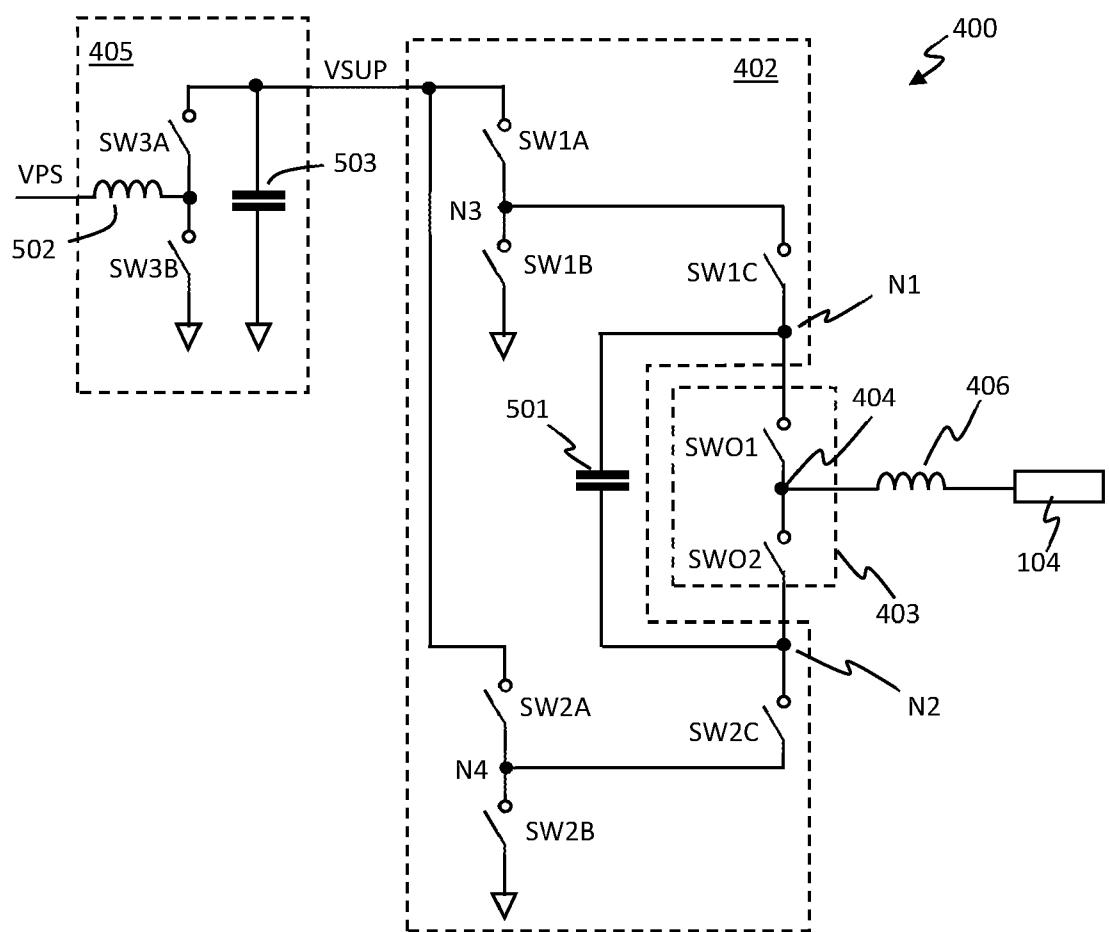


Figure 5

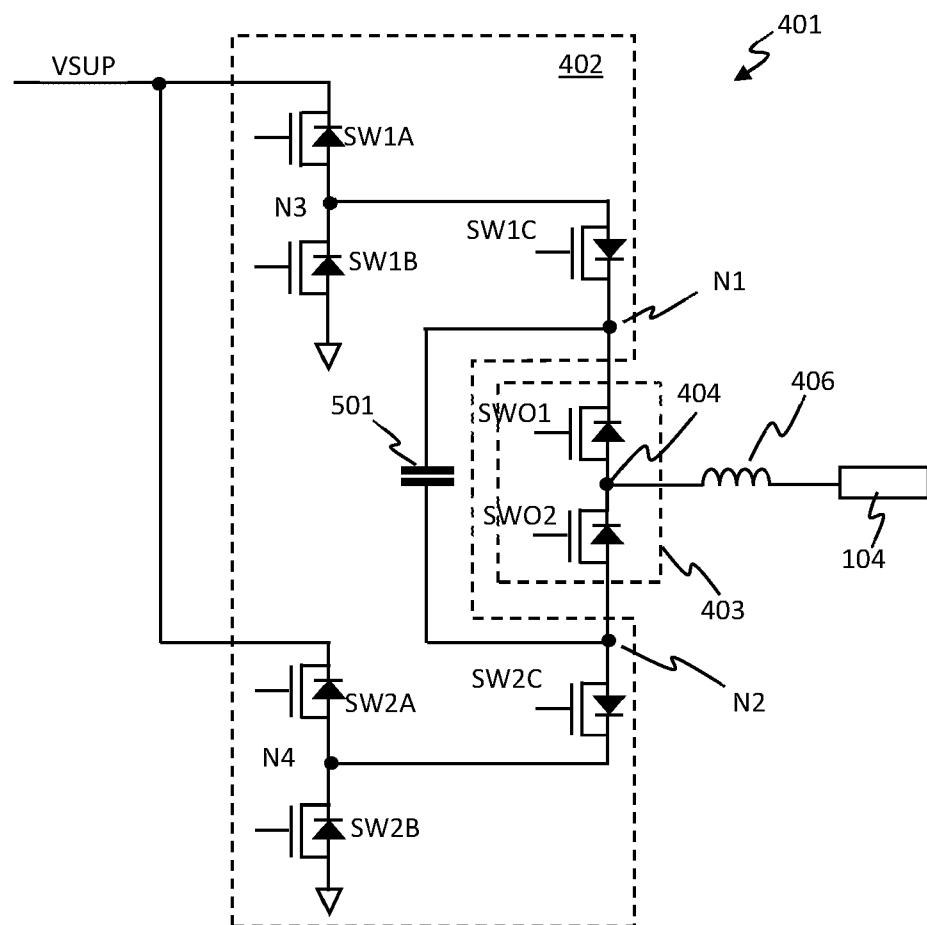


Figure 6

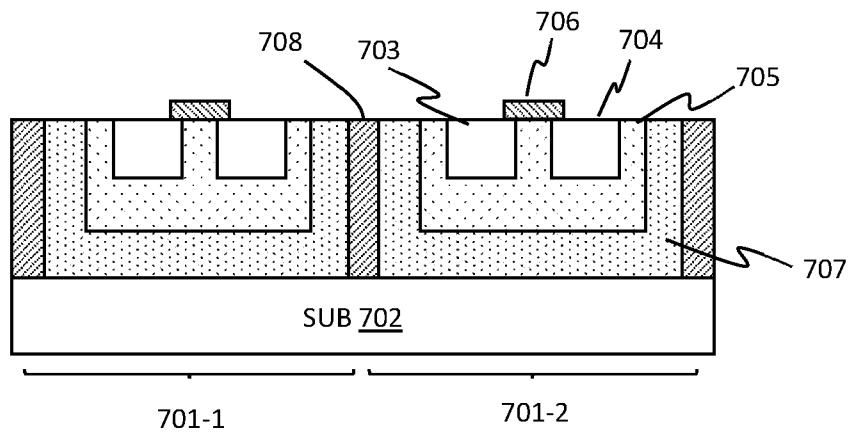


Figure 7

	Switch and State	Source/bulk Voltage	Drain Voltage	NWell Voltage
<b>Mode 1</b> <b>0V to +VSUP</b>	SW1A ON	+VSUP	+VSUP	+VSUP
	SW1B OFF	0V	+VSUP	+VSUP
	SW1C ON	+VSUP	+VSUP	+VSUP
	SWO1 DC	0V/+VSUP	+VSUP	+VSUP
	SWO2 DC	0V	0V / +VSUP	0V
	SW2A OFF	0V	+VSUP	0V
	SW2B ON	0V	0V	0V
	SW2C ON	0V	0V	0V
<b>Mode 2</b> <b>+VSUP to +2VSUP</b>	SW1A ON	+ VSUP	+VSUP	+VSUP
	SW1B OFF	0V	+VSUP	+VSUP
	SW1C OFF	+VSUP	+2VSUP	+2VSUP
	SWO1 DC	+VSUP /+2VSUP	+2VSUP	+2VSUP
	SWO2 DC	+VSUP	+VSUP/+2VSUP	+VSUP
	SW2A ON	+VSUP	+VSUP	+VSUP
	SW2B OFF	0V	+VSUP	+VSUP
	SW2C ON	+VSUP	+VSUP	+VSUP
<b>Mode 3</b> <b>-VSUP to 0V</b>	SW1A OFF	0V	+VSUP	+VSUP
	SW1B ON	0V	0V	0V
	SW1C ON	0V	0V	0V
	SWO1 DC	-VSUP/0V	0V	0V
	SWO2 DC	-VSUP	-VSUP/0V	0V
	SW2A OFF	0V	+VSUP	+VSUP
	SW2B ON	0V	0V	+VSUP
	SW2C OFF	-VSUP	0V	0V

Figure 8

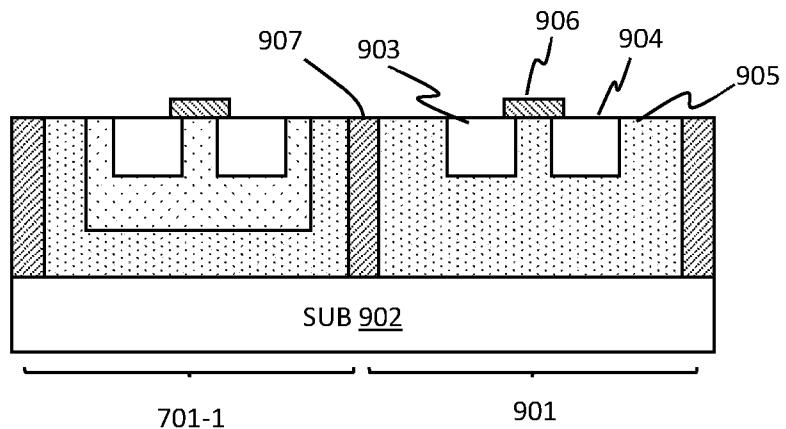


Figure 9

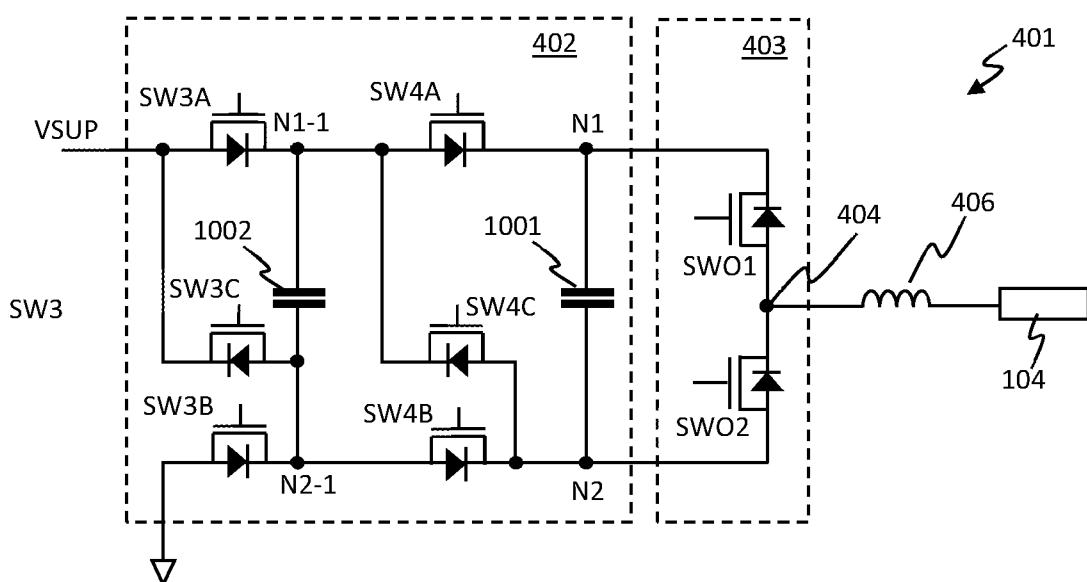


Figure 10

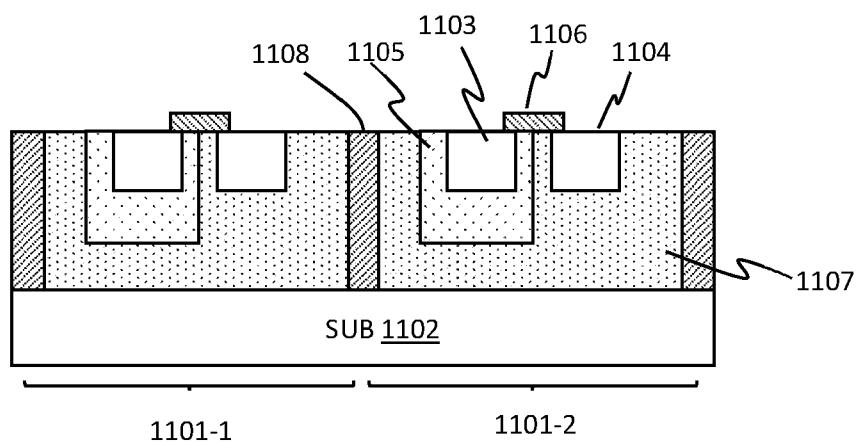


Figure 11

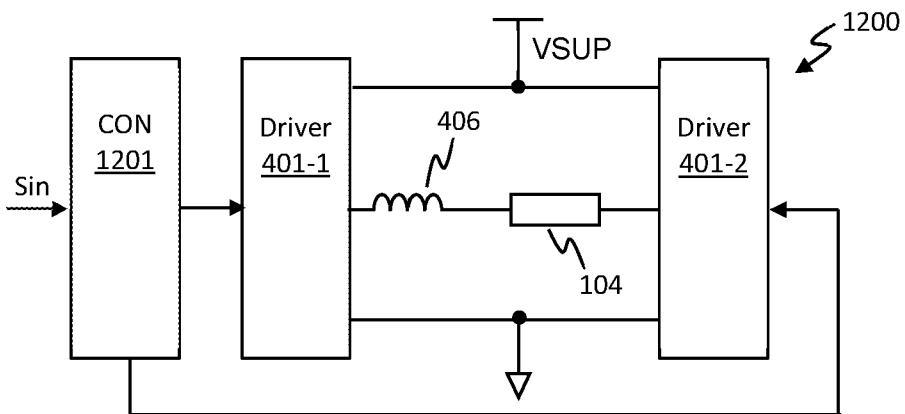


Figure 12

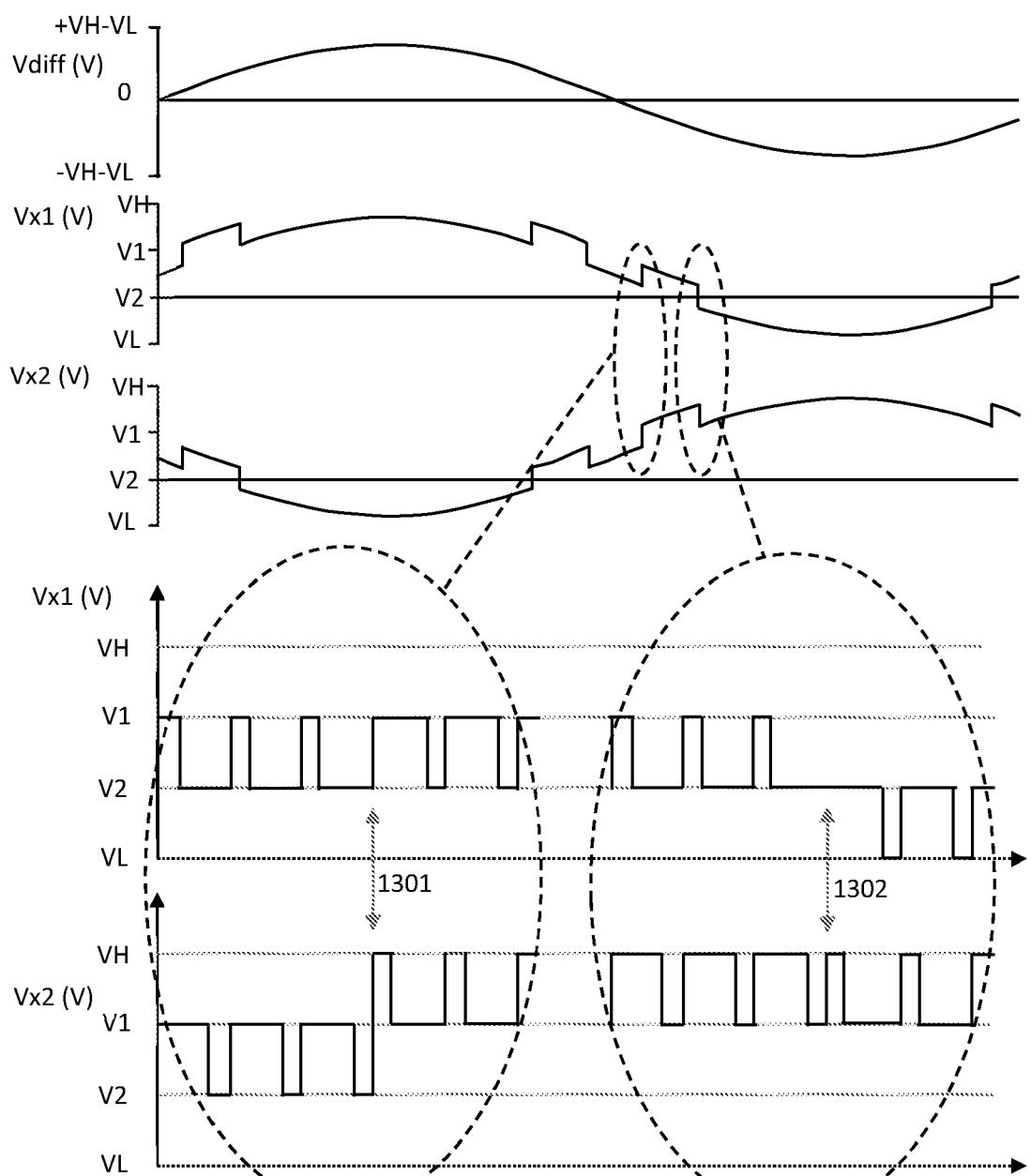


Figure 13

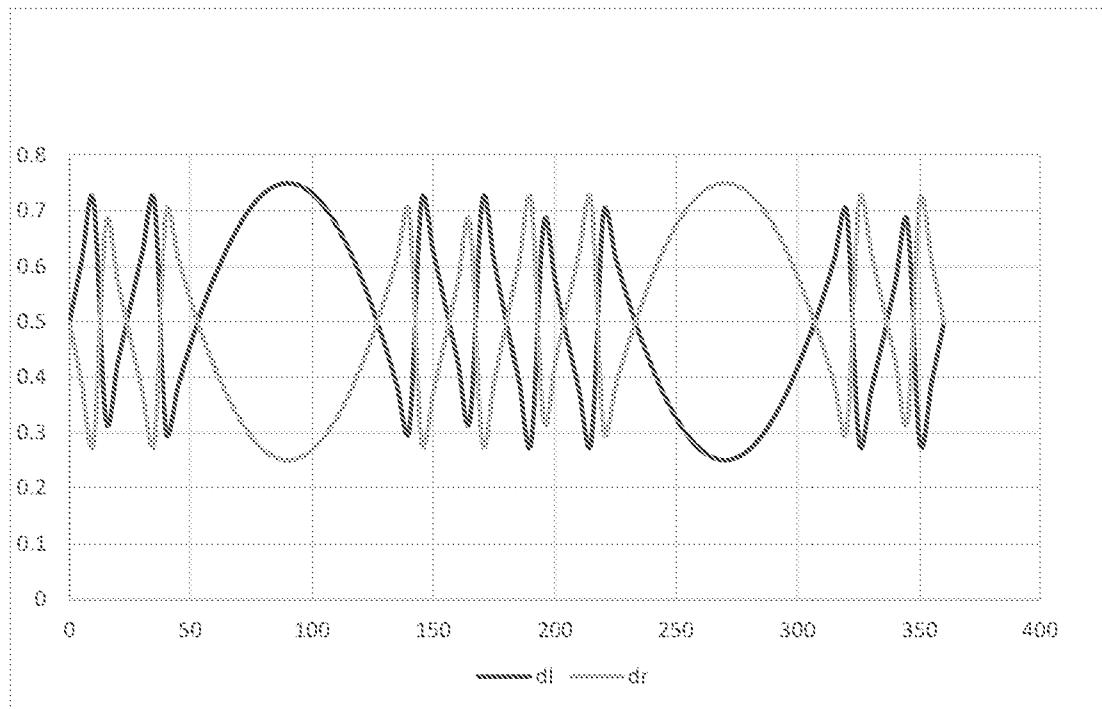


Figure 14

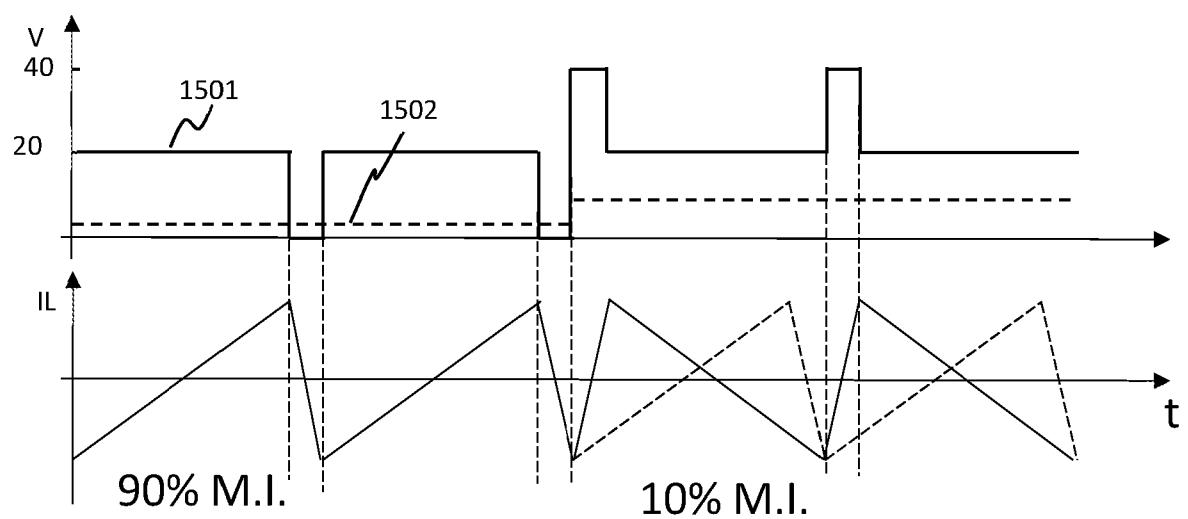


Figure 15

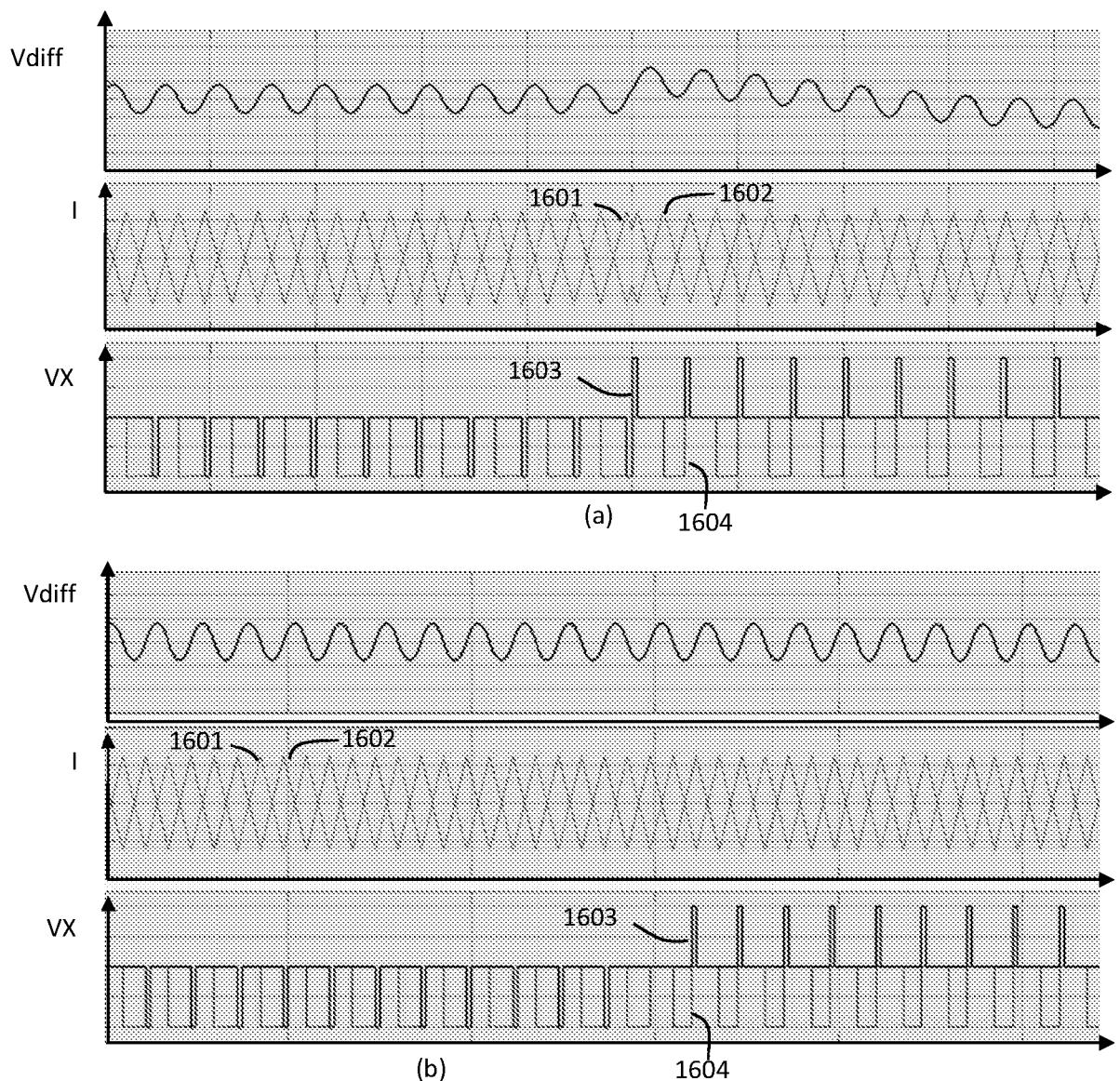


Figure 16

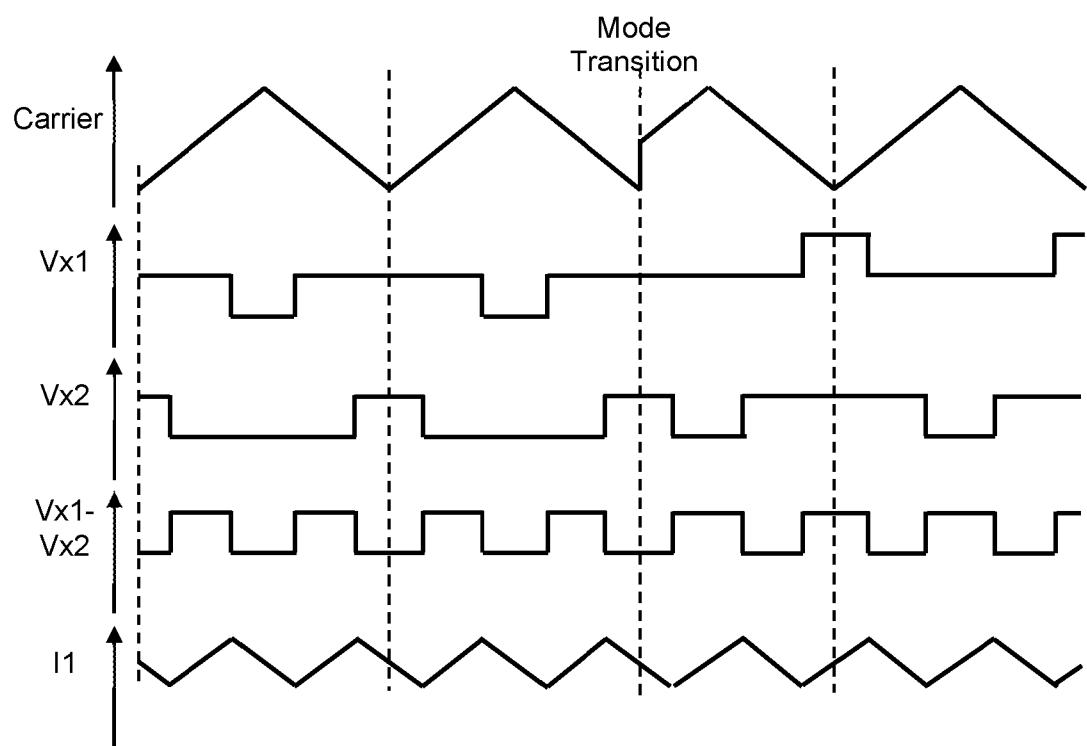
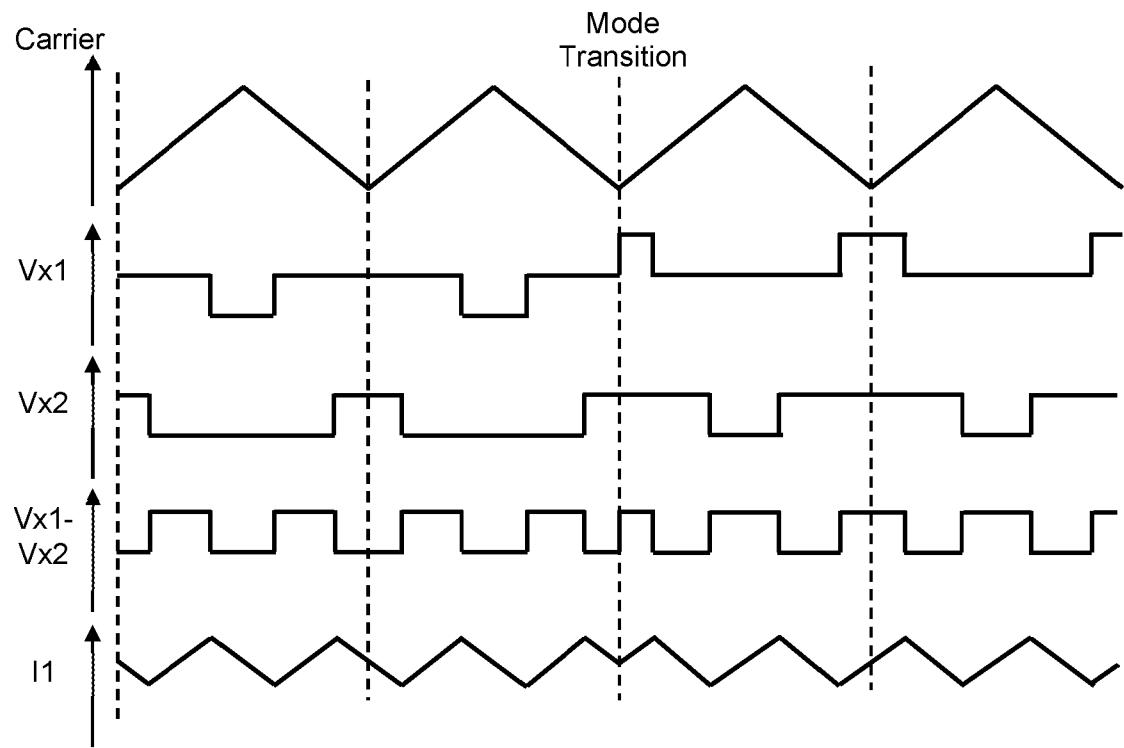


Figure 17

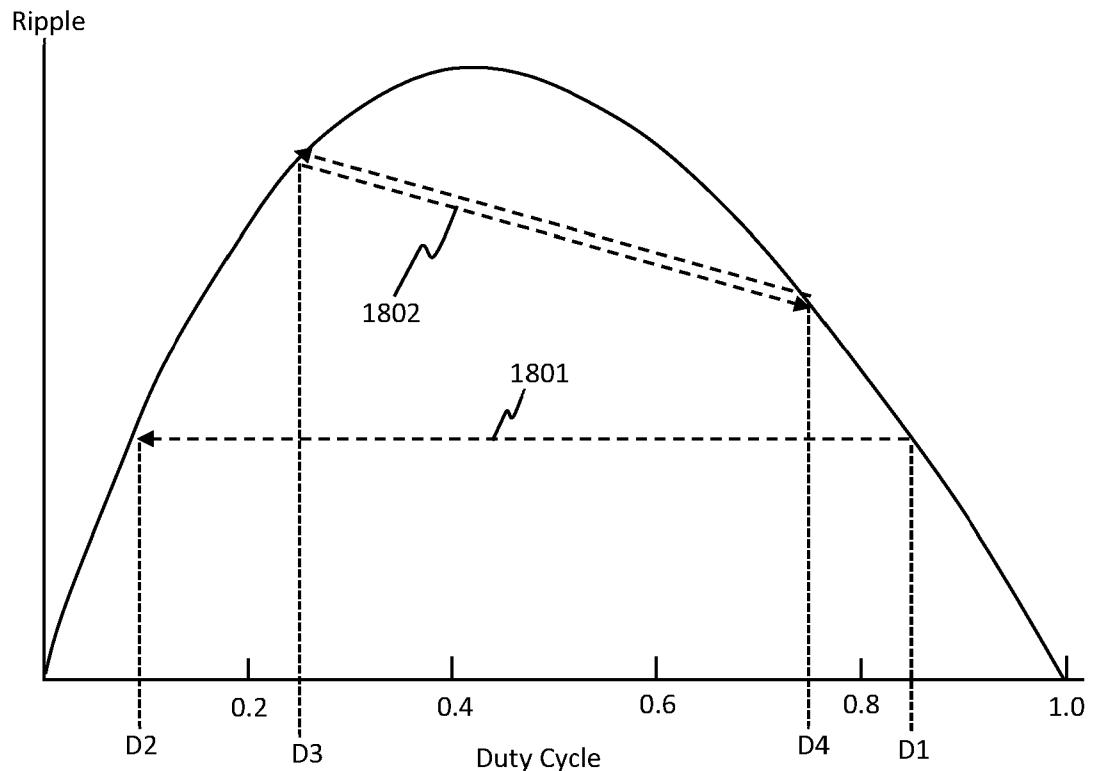


Figure 18

## DRIVER CIRCUITRY AND OPERATION

The field of representative embodiments of this disclosure relates to methods, apparatus and/or implementations concerning or relating to driver circuits, and in particular to  
5 switching driver circuits as may be used to drive a transducer.

Many electronic devices include transducer driver circuitry for driving a transducer with a suitable driving signal, for instance for driving an audio output transducer of the host device or a connected accessory, with an audio driving signal.

10

**Figure 1** is a schematic illustration of circuitry for driving a transducer. As shown generally at 100 in figure 1, a driver 102 may receive an input signal  $S_{in}$  and generate a corresponding drive signal for driving the transducer. The input signal  $S_{in}$  may, for example, be an input audio or ultrasonic signal or haptic waveform or the like and may  
15 be received from upstream circuitry (not shown) such as upstream amplification and/or signal processing circuitry. The driver 102 drives the transducer 104 with the drive signal based on the input signal  $S_{in}$ . Where the transducer is an output transducer the driver 102 drives the transducer 104 to cause the transducer to produce a desired output, e.g. an audible, ultrasonic or haptic output based on the input signal  $S_{in}$ .

20

In some applications the driver 102 may include a switching amplifier stage, e.g. a class-D amplifier stage or the like, for generating the drive signal. Switching amplifier stages can be relatively power efficient and thus can be advantageously used in some applications. A switching amplifier stage generally operates to switch an output node  
25 between defined high and low switching voltages, with a duty cycle that provides a desired average output voltage over the course of the duty cycle for the drive signal. To provide a desired output voltage range, the switching amplitude may be switched between the peak high and low voltages of the desired output range, for instance between a high-side voltage  $V_H$  and ground.

30

Figure 1 illustrates an example of a single-ended driver, but it will be understood that in some implementations a transducer may be driven in a bridge-tied-load configuration.

**Figure 2** illustrates an example of driver circuitry 200 for driving a bridge-tied-load (BTL).

Figure 2 illustrates that each side of the load 104 is connected to a respective driver 102-1 and 102-2. The output node 201 of each driver 102-1 and 102-2 is switched between a high-side voltage VH and a low-side voltage VL, for example between a

5 positive supply voltage and ground, with controlled duty cycles so as to control the voltage across the load 104. Figure 2 illustrates that each of the drivers 102-1 and 102-2 comprise switches 202a and 202b, which may be typically implemented as MOSFETs, for selectively connecting the output node 201 of the driver to the high-side voltage or the low-side voltage. Modulators 203-1 and 203-2 control the duty-cycle of the switching  
10 of the switches 202a and 202b of the respective driver 102-1 and 102-2 based on the input signal. The modulators 105 may generate PWM or PDM switching signals based on the input signal as will be understood by one skilled in the art. The drivers 102-1 and 102-2 can thus be seen as generating respective first and second drive signals which are components of a differential driving signal for driving the load.

15

In at least some applications, for example for driving some piezoelectric transducers, it may be desirable to generate drive signals with relatively high amplitudes, for example with a peak-to-peak voltage range of the order of tens of volts or so. This may therefore typically require the input voltage for the driver 102, i.e. the voltage difference between  
20 VH and VL, to be relatively high to provide the required output range.

For instance, piezoelectric or piezo transducers or ceramic transducers are increasingly being proposed for use in some applications, for instance for audio, ultrasonic or haptics output, and may be considered as an alternative to conventional cone and voice-coil type

25 speaker or resonant actuators or the like. Piezoelectric transducers may be advantageous in some applications, especially for portable electronics devices such as mobile telephones, laptop and tablet computers and the like, due to their thin form factor, which may be beneficial in meeting the demand for increasing functionality in such devices without significantly increasing their size. Piezoelectric transducers are also  
30 increasingly finding application as transducers for ultrasonic and range-finding systems. Piezoelectric transducers may also be used as input transducers or sensors in some applications.

Using such high input voltages can, however, result in relatively large voltage stresses across the switches of the driver, which may require the use of devices with high voltage tolerances, which may not be practical for some applications, or which may add to the cost of the circuitry.

5

Using such high input voltages as the switching voltages for the switching drivers may also, in some implementations, require the use of components such as inductors with a relatively high inductances so as to avoid large ripple current due to the switching, which may be disadvantageous in some implementations.

10

Embodiments of the present disclosure relate to improved driving circuits.

According to an aspect of the disclosure there is provided a switching driver for driving a transducer comprising: first and second supply nodes for connection to first and second voltage supplies defining an input voltage; an output bridge stage comprising a first output switch connected between a first switching voltage node and an output node and a second output switch connected between a second switching voltage node and the output node; a capacitor; and a network of switches connecting said first and second supply nodes with said first and second switching voltage nodes and said capacitor. The network of switches may be operable in different switch states to provide different voltages at the first and second switching voltage nodes. The switch states may comprise a first switch state in which the capacitor is connected between the first and second supply nodes to be charged to the input voltage and the first and second switching voltage nodes are coupled to the first and second supply nodes respectively; and a second switch state in which the second switching voltage node is connected to a voltage different to that at the second supply node and the capacitor is connected between the second switching voltage node and the first switching voltage node to provide a boosted voltage at the first switching node. The driver may also comprise a controller configured to control the switch state of the network of switches and a duty cycle of the first and second output switches of the output bridge stage based on an input signal to generate an output signal at the output node for driving the transducer.

In some examples, in the second switch state, the second switching voltage node is connected to the first supply node. The network of switches may be further operable in

a third switch state in which the first switching voltage node is connected to the second supply node and said capacitor is connected between the second supply node and the second switching voltage node to provide a boosted voltage at the second switching node. The first voltage supply may be more positive than the second voltage supply and

- 5 the controller may be configured to operate: in the first switch state in a first mode of operation to provide a drive signal at the output node in a range between the first and second voltage supplies; in the second switch state in second mode of operation to provide a drive signal at the output node in a range between the first voltage supply and the first voltage supply boosted positively by the input voltage; and in the third switch
- 10 state in a third mode of operation to provide a drive signal at the output node in a range between the second voltage supply and the second voltage supply boosted negatively by the input voltage.

In some examples, the network of switches may be configured such that, in use, a  
15 voltage difference across any of the switches of the network of switches and the first and second output switches is not substantially greater in magnitude than the input voltage.

The network of switches may be configured such a first electrode of the capacitor can be selective connected to either of the first or second supply nodes. The network of  
20 switches may be configured such that a second electrode of the capacitor can be selectively connected to either of the first or second supply nodes. In some examples, the capacitor may be connected between the first and second switching voltage nodes in parallel with the output bridge stage. The network of switches may comprises: a first switch connecting the first supply node to a first supply select node; a second switch connecting the second supply node to the first supply select node; a third switch connecting the first supply select node to the first switching voltage node; a fourth switch connecting the first supply node to a second supply select node; a fifth switch connecting the second supply node to the second supply select node; and a sixth switch connecting the second supply select node to the second switching voltage node.

30

The controller may be configured such that, when operating in the second switch state: the fourth switch and sixth switch are closed, with the fifth switch open, to connect the first supply node to the second switching voltage node; and the second and third switches are open, with the first switch closed, so as to disconnect the first switching

voltage node from the first and second supply nodes and to limit the voltage difference across any of the first to third switches to be not substantially greater than the input voltage.

5 The capacitor may have a capacitance which is large enough to store sufficient charge to supply the transducer through a cycle of the input signal.

In some examples, the capacitor is a first capacitor, and the switching driver may further comprises a second capacitor. In at least one of the first and second switch states, the

10 second capacitor may be connected between the first and second voltage supplies to be charged to the input voltage. In the second switch state, the second switching voltage node may be connected to the first supply node. The switch network may be further operable in a third switch state in which the second capacitor is connected between the first supply node and the second switching voltage node to provide a boosted voltage at  
15 the second switching node and the first capacitor is connected between the second switching voltage node and the first switching voltage node to provide a further boosted voltage at the first switching voltage node. The first capacitor may be connected between the first and second switching voltage nodes in parallel with the output bridge stage.

20 In some examples, at least one of the switches of the network of switches and the first and second output switches comprises an NMOS transistor where at least part of the NMOS transistor is formed within an N-well in a substrate and wherein the switching driver is configured such that the N-well of the NMOS transistor is, in use, driven with a voltage based on the voltages at the first and second switching voltage nodes.

25

In some examples, the switching driver may be a first switching driver and a switching driver circuit may further comprise a second switching driver, the first and second switching drivers being configured to drive the transducer in a bridge-tied load configuration. The second switching driver may comprise an output bridge stage, a  
30 capacitor and a network of switches operable in the same way as the first switching driver. The controller may be configured to control the switch state of the network of switches and duty cycles of the output bridge stages of both the first and second switching drivers based on an input signal to generate a differential output signal.

In some examples a switching driver circuit may comprising the switching driver of any of the embodiments described herein and a DC-DC converter configured to receive at least one input voltage supply and to generate at least one of said first and second voltage supplies.

5

In some examples an inductor may be connected to the output node for connection in series with the transducer.

10 Embodiments also relate to a switching driver circuit comprising a switching driver of any of the embodiments and the transducer. The transducer may be at least one of an audio output transducer and a haptic output transducer. The transducer may be a piezoelectric or ceramic transducer. Embodiments also relate to an electronic device comprising such a switching driver.

15 In another aspect there is provided a switching driver for driving a transducer based on an input signal comprising: first and second supply nodes for connection to first and second voltage supplies defining an input voltage; an output bridge stage comprising a first output switch connected between a first switching voltage node and an output node and a second output switch connected between a second switching voltage node and the output node; a capacitor connected between said first and second switching voltage nodes in parallel with the output bridge stage; and a network of switches connecting said first and second supply nodes with said first and second switching voltage nodes, the network of switches being operable in different switch states. In a first switch, the first and second switching voltage nodes may be coupled to the first and second supply nodes respectively and the capacitor is charged to the input voltage. In a second switch state, the second switching voltage node may be connected to a voltage different to that at the second supply node and the capacitor is connected between the second switching voltage node and the first switching voltage node to provide a boosted voltage at the first switching node.

20

25

30 Aspects also relate to a switching driver for driving a transducer comprising: first and second supply nodes for connection to first and second voltage supplies defining an input voltage; an output bridge stage for selectively connecting an output node to first or second switching voltage nodes with a controlled duty cycle; a capacitor connected

between said first and second switching voltage nodes in parallel with the output bridge stage; and a network of switches connecting said first and second supply nodes with said first and second switching voltage nodes, wherein the network of switches is operable such that a first electrode of said capacitor can be selectively connected to 5 either of the first and second supply nodes.

In a yet further aspect, there is provided a driver circuit for driving a transducer based on an input signal comprising: first and second switching drivers with respective driver output nodes for driving said transducer in a bridge-tied-load configuration, each of the 10 first and second switching drivers comprising a respective output stage for controllably switching the respective driver output node between high and low switching voltages with a controlled duty cycle. Each of the first and second switching drivers is operable in a plurality of different driver modes, wherein the switching voltages are different in said different driver modes; and a controller controls the driver mode of operation and the 15 duty cycle of each of the first and second switching drivers based on the input signal. The controller is configured to control the duty cycles of the first and second switching drivers within defined minimum and maximum limits of duty cycles. The controller is configured to transition between different driver modes of operation when the duty cycle of at least one of the first and second switching drivers reaches the maximum or minimum 20 duty cycle limit and the controller is configured to implement the transition by changing the driver mode of one of the first and second switching drivers at said maximum or minimum limit of duty cycle and vary the duty cycle of that one of the first and second switching drivers to the other limit of duty cycle whilst maintaining the driver mode of the other of the first and second switching drivers and applying a variation in duty cycle to 25 maintain a magnitude of a differential component of the first and second driver signal.

In some examples, the maximum limit of duty cycle may be 95% or less. The minimum limit of duty cycle may be 5% or greater.

30 In some examples the difference between the switching voltages may be the same in each of the different driver modes.

In some examples, each of the first and second switching drivers may be operable in: a first mode in which the switching voltages are a first voltage V1 and a second voltage

V2, where the first voltage is more positive than the second voltage; and at least one of: a second mode in which the switching voltages are the first voltage V1 and a voltage which is more positive than the first voltage V1; and a third mode in which the switching voltages are the second voltage V2 and a voltage which is more negative than the 5 second voltage V2. Each of the first and second switching drivers may have first and second supply nodes for receiving first and second supply voltages, and the first and second switching drivers may be configured such that the first voltage V1 and the second voltage V2 are equal to the supply voltages received at the respective first and second supply nodes. The controller may be configured to control the driver modes of the first 10 first and second switching drivers to provide a plurality of BTL modes. The BTL modes may comprise a low-signal mode in which both the first and second switching drivers operate in the first driver mode; an intermediate-signal mode in which one of the first and second switching drivers operate in the first driver mode and the other one of first and second switching drivers operates in either the second driver mode or the third driver mode; 15 and/or a high-signal level mode in which one of the first and second switching drivers operates in the second driver mode and the other one of first and second switching drivers operates in the third driver mode. The controller may be configured such that, in each of the BTL modes of operation, the controller controls the duty cycles of the first and second switching drivers so that a common-mode component of first and second 20 drive signals at the respective driver output nodes of the first and second switching drivers does not substantially vary with signal level. The controller may be configured such that the common-mode component of first and second drive signals when operating in the low-signal mode is substantially the same as the common-mode component of the first and second drive signals when operating in the high-signal mode, but different to 25 the common-mode component of first and second drive signals when operating in the intermediate-signal mode.

In some examples, the controller may be configured to control the duty cycles of the first and second switching drivers before and after a transition in mode such that a common- 30 mode component of the voltage across the transducer differs before and after the transition.

Each of the first and second switching drivers may comprise a variable boost stage selectively operable to provide voltage boosting to provide a voltage for use as a

switching voltage in at least one of the different driver modes. Each of the first and second switching drivers may comprise first and second supply nodes for receiving first and second supply voltages and the variable boost stage of each of the first and second switching drivers may comprise at least one capacitor and a network of switches for

5 connecting the first and second supply nodes with the capacitor and the respective output stage. The network of switches may be operable in one switch state in which the at least one capacitor is connected between the first and second supply nodes to be charged to the input voltage and in at least one switch state where the at least one capacitor is connected in series with one of the first and second supply nodes to provide

10 a boosted voltage as one of the switching voltages.

In some examples, the driver circuit may further comprise at least a first inductor connected to the driver output node of the first switching driver for connection in series with the transducer.

15 In a further aspect, there is provided a driver circuit for driving a transducer based on an input signal comprising: first and second switching drivers configured to drive the transducer in a bridge-tied-load configuration; wherein each of the first and second switching drivers comprise an output stage for controllably switching a driver output node

20 two switching voltages with a controlled duty cycle and wherein each of the first and second switching drivers is operable in a plurality of different driver modes where the switching voltages are different in the different driver modes. A controller may control the driver mode of operation and duty cycle of each of the first and second switching drivers based on the input signal, wherein the controller is configured to controllable vary

25 the duty cycle within a minimum duty cycle limit greater than 0% and a maximum duty cycle limit less than 100% and to transition between driver modes when one of the minimum or maximum duty cycle limits is reached. The controller may be configured such that during any mode transition, the driver mode of just one of the first and second switching drivers is changed.

30 In a further aspect, there is provided a driver circuit for driving a transducer based on an input comprising: first and second switching drivers for generating respective first and second drive signals at first and second output nodes for driving the transducer in a bridge tied load configuration, wherein each of the first and second switching drivers is

configured to controllably switch the respective first or second output node between two switching voltages with a controlled duty cycle; and wherein the first and second switching drivers are configured such that the two switching voltages are controllably variable to provide different BTL modes of operation. The driver circuit may be

5 configured so as to transition between modes by: controllably varying the switching voltages for one of the first and second switching drivers whilst switching the duty cycle of that driver from one of a maximum or minimum limit of duty cycle to the other or the maximum or minimum limit; whilst maintaining the switching voltages for the other of the first and second switching drivers and applying a corresponding change in duty cycle to

10 maintain a differential voltage.

In a further aspect there is provided a driver apparatus for driving a transducer comprising a first switching driver having a first driver output node for driving the transducer. The first switching driver comprises a first output bridge stage for selectively

15 switching the first driver output node between high and low switching voltages, a first modulator for controlling a duty cycle of switching of the first output bridge stage based on an input signal; and a first voltage controller for providing said switching voltages. The first switching driver is operable in a plurality of driver modes of operation in which the first voltage controller is operable to provide different switching voltages in each

20 driver mode. The apparatus also comprises a controller for controlling the driver mode of operation and the duty cycle of the first switching driver based on the input signal, wherein the controller is configured to transition between said driver modes of operation from a present mode to a new mode by: controlling the first voltage controller to provide the switching voltages for the new mode; and controlling the first modulator to vary the

25 duty cycle of the first output bridge stage, wherein the change in duty cycle is controlled such that there is no substantial discontinuity in switching ripple.

In some examples, the driver apparatus may also comprise a second switching driver having a second driver output node for driving the transducer in a bridge-tied load

30 configuration with the first switching driver. The second switching driver may comprise a second output bridge stage for selectively switching the second driver output node between respective high and low switching voltages and a second modulator for controlling a duty cycle of switching of the second output bridge stage based on the input signal. The controller may be configured, on a transition in mode of operation of the first

switching driver from the present mode to the new mode, to operate the second switching driver with no change to the switching voltages for the second output bridge stage and to control the second modulator to vary the duty cycle of the second output bridge stage such that a differential voltage across the transducer over the course of a switching cycle

5 is substantially the same before and after the transition. On such a transition of the first switching driver from the present mode to the new mode, the controller may be configured to control the first modulator to vary the duty cycle of the first output bridge stage by a first duty cycle amount and to vary the duty cycle of the second output bridge stage by a second duty cycle amount, wherein the magnitude of the first duty cycle

10 amount added to the magnitude of the second duty cycle amount corresponds to a duty cycle of 100%.

The controller may be configured to operate the first switching driver in a selected driver operating mode with a duty cycle for the first output bridge stage within predetermined

15 maximum and minimum limits of duty cycle. The controller may be configured to transition from the present mode to the new mode when the relevant duty cycle limit is reached. The controller may be configured to, when the relevant maximum or minimum duty cycle limit is reached for the present mode of operation, to transition to the new mode of operation and to control the first modulator to operate at the minimum or

20 maximum duty cycle limit respectively in the new mode of operation. In some examples the maximum duty cycle limit may be 75%. In some examples, the minimum duty cycle limit may be 25%.

In some implementations, the controller may be configured to control the first and second

25 switching drivers such that there is no substantially change in ramp direction in load current from the first driver output node at the point in time in which the first voltage controller varies the switching voltages to the switching voltages corresponding to the new mode.

30 Each of the first and second modulators may compare a modulator input, based on the input signal, with a carrier waveform to control the duty cycle of the respective output stage. The controller may be configured, on a change in operating mode of the first switching driver, to vary an amount of a mode correction applied to the modulator input by an amount related to the switching voltages of the new operating mode. In some

examples, on a transition of the first switching driver from the present mode to the new node, the controller may be configured to apply a phase shift to the carrier waveform. The phase shift applied to the carrier waveform may be based on the amount of change in duty cycle for the second switching driver. In some cases the carrier waveform may

- 5 be a triangle waveform that ramps from a minimum value to a maximum value and back to the minimum value over the course of a cycle period. In such a case, the controller may be configured such that the phase shift applied to the carrier waveform is a proportion of the cycle period that corresponds to half the change in duty cycle for the second switching driver.

10

In some implementations the second switching driver may comprise a second voltage controller for providing the switching voltages for the second output bridge stage and the second switching driver may also be operable in a plurality of driver modes of operation in which the second voltage provides different switching voltages in each driver mode.

- 15 The controller may also control the driver mode of operation of the second switching driver based on the input signal. The controller may be configured to transition between the driver modes of operation of the second switching driver from a present mode and a new mode by: controlling the second voltage controller to provide the switching voltages for the new mode; controlling the second modulator to vary the duty cycle of the second
- 20 output bridge stage; and operating the first switching driver with no change to the switching voltages for the first switching driver and controlling the first modulator to vary the duty cycle of the first output stage such that a differential voltage across the transducer over the course of a switching cycle is substantially the same before and after the transition.

25

In some implementations, the first switching driver may be configured to drive one side of the transducer in a single-ended configuration with an opposite side of the transducer connected to a DC voltage. In such a case, the controller may be configured, on a transition in driver mode of operation of the first switching driver from the present mode to the new mode, to controllably vary the value of the DC voltage such that a differential voltage across the load over the course of a switching cycle is substantially the same before and after the transition.

In some implementations the driver apparatus may further comprise at least a first inductor connected to the first driver output node for connection in series with the transducer.

5 In some examples the transducer may be at least one of: an audio output transducer; a haptic output transducer; a piezoelectric transducer; and a ceramic transducer.

Aspects also relate to an electronic device comprising the driver apparatus of any of the embodiments described herein.

10

In another aspect there is provided a driver apparatus comprising a first switching output stage for switching a first driver output node between a set of switching voltages with a controlled duty cycle wherein the driver apparatus is operable in at least first and second modes of operation. In the first mode of operation the set of switching voltages comprise

15 a first voltage and a second voltage, and in the second mode of operation the set of switching voltages comprise the second voltage and a third voltage. The driver apparatus further comprises a controller for controlling the mode of operation of the driver apparatus and the duty cycle of the first switching output stage based on an input signal.

The controller is configured to transition between the first and second mode of operations

20 from a present mode to a new mode by: controlling the driver apparatus in the present mode with a first duty cycle, controllably varying the set of switching voltages to the relevant voltages for the new mode of operation; and controllably varying the duty cycle of the first switching output stage, wherein the change in duty cycle is controlled such that there is substantially no discontinuity in switching ripple.

25

In a further aspects there is provided a driver apparatus for driving a transducer in a bridge-tied-load configuration between first and second driver output nodes with a differential drive signal based on an input signal. The driver apparatus comprises a first switching driver for switching the first driver output node between a first set of switching

30 voltages and a second switching driver for switching the second driver output node between a second set of switching voltages. At least the first switching driver is operable in different driver modes in which the first set of switching voltages is different in the different driver modes. A controller is configured to control a duty cycle of the first switching driver and a duty cycle of the second switching driver by comparing a carrier

signal with at least one modulator input signal that varies with the input signal. On a change of driver mode of the first switching driver, the controller is configured to adjust an offset applied to at least one modulator input signal and also apply a phase shift to the carrier waveform.

5

In a further aspect, there is provided a driver circuit for driving a transducer based on an input signal comprising: first and second supply nodes for receiving an input voltage; first and second switching drivers with respective driver output nodes for driving said transducer in a bridge-tied-load configuration, each of the first and second switching 10 drivers comprising a respective output stage for controllably switching the respective driver output node between high and low switching voltages with a controlled duty cycle to provide respective first and second drive signals. Each of the first and second switching drivers may be operable such that the high and low switching voltages can be controllably varied in at least three different driver modes. In a first driver mode the high 15 switching voltage is at a first voltage level V1 and the low switching voltage is at a second voltage level V2, and the first and second voltage levels differ by an amount equal to the input voltage. In a second driver mode the low switching voltage is at the first voltage level V1 and the high switching voltage is higher than the first voltage level V1 by an amount equal to the input voltage. In a third driver mode the high switching voltage is at 20 the second voltage level V2 and the low switching voltage is lower than the second voltage level V2 by an amount equal to the input voltage. A controller may control the driver mode and duty cycle of each of the first and second switching drivers based on the input signal, wherein the controller is operable in a plurality of BTL modes of operation comprising: a low-signal BTL mode to operate both the first and second switching drivers 25 in the first driver mode; an intermediate signal BTL mode to operate one of the first and second switching drivers in the first driver mode and the other of first and second switching drivers in one of the second or third driver mode; and a high-signal BTL mode to operate one of the first and second switching drivers in the second driver mode and the other of first and second switching drivers in the third driver mode.

30

Embodiments also relate to a driver circuit of any of the embodiments described herein comprising the transducer. The transducer may be at least one of an audio output transducer and a haptic output transducer. The transducer may be a piezoelectric or ceramic transducer.

Embodiments also relate to an electronic device comprising a driver circuit of any of the embodiments described herein.

- 5 It should be noted that, unless expressly indicated to the contrary herein or otherwise clearly incompatible, then any feature described herein may be implemented in combination with any one or more other described features.

For a better understanding of examples of the present disclosure, and to show more clearly how the examples may be carried into effect, reference will now be made, by way of example only, to the following drawings in which:

5 Figure 1 illustrates one example of a single-ended driving circuit for driving a load;

Figure 2 illustrates one example of a driver circuit for driving a load in a bridge-tied-load configuration;

10 Figure 3 illustrates example output waveforms of a switching driver according to an embodiment;

Figure 4 illustrates one example of a driver circuit according to an embodiment;

15 Figure 5 illustrates one example of the driver circuit of figure in more detail;

Figure 6 illustrates one example of a MOSFET implementation of a switching driver;

20 Figure 7 illustrates one example of NMOS devices suitable for use in the switching driver of figure 6;

Figure 8 illustrates one example of suitable operating voltages for different modes of operation;

25 Figure 9 illustrates an example of one example of NMOS and PMOS devices suitable for use in the switching driver of figure 6;

Figure 10 illustrates another example of an implementation of a switching driver;

30 Figure 11 illustrates NMOS devices suitable for use in the switching driver of figure 10;

Figure 12 illustrates a driver circuit in a bridge-tied-load configuration;

Figure 13 illustrates example waveforms for the drivers on each side of the load and the resultant differential voltage for a bridge-tied load configuration;

Figure 14 illustrates how the duty-cycles of the switching drivers on each side of the load

5 may vary for the differential waveform illustrated in figure 13;

Figure 15 illustrates example waveforms for a mode transition for a single-ended driver;

Figure 16 illustrates one example of waveforms for a driver circuit for driving a bridge-

10 tied-load;

Figure 17 illustrates examples waveforms across a mode transition; and

Figure 18 illustrates one example illustrates duty cycle of the switching drivers may be

15 controllably varied to manage discontinuities.

The description below sets forth example embodiments according to this disclosure.

20 Further example embodiments and implementations will be apparent to those having ordinary skill in the art. Further, those having ordinary skill in the art will recognize that various equivalent techniques may be applied in lieu of, or in conjunction with, the embodiments discussed below, and all such equivalents should be deemed as being encompassed by the present disclosure.

25

Embodiments of the disclosure relate to driver circuitry for driving a transducer and, in particular, to driver circuitry suitable for driving a reactive load such as a piezoelectric transducer, although embodiments may be implemented to drive other types of transducer. Embodiments of the disclosure also relate to methods of operation of driver

30 circuitry.

At least some embodiments of the present disclosure relate to switching drivers for generating a drive signal at a driver output node. The switching driver is operable in a plurality of different driver operating modes, wherein, in each of the different driver

operating modes, the output node is switched between two switching voltages, where the switching voltages are different in the different modes of operation. Thus, in a given driver mode of operation, the switching driver operates to switch the driver output node between the relevant switching voltages with a controlled duty cycle so as to provide the

- 5 drive signal with an average voltage (over the course of a cycle period) within a voltage range defined by the switching voltages. However, in a different driver mode of operation, the switching voltages are different so as to provide, in that driver mode, a different voltage range for the drive signal. The overall output voltage range for the switching driver may thus be defined by the different driver modes of operation, and each
- 10 individual driver mode of operation may provide only part of the overall output voltage range, that is, the voltage range between the two switching voltages in a given mode forms only a part or a subset of the overall output voltage range.

The switching driver thus switches between two defined switching voltages with a

- 15 controlled duty cycle to provide the drive signal at the driver output node with a desired average output voltage. In use, the average output voltage can vary within a defined voltage range between a peak high voltage VH and a peak low voltage VL. However, rather than switch a driver output node between these peak high and low voltage levels of the output range, as would be conventional for the drivers discussed with respect to
- 20 figures 1 and 2, the switching driver of embodiments of the disclosure switches between two switching voltages which form a subset, or only part, of the full output range between VH and VL. Thus, in each driver mode of operation, the output node is switched between two switching voltages that differ from one another by less than the full output range, but the full output range can be provided by varying the driver mode of operation, as
- 25 necessary.

In effect, the switching driver may be considered to operate with variable voltage rails, where the voltage rails are controllably varied to provide different operating ranges in the different operating modes, where each of the operating ranges is only part of the of full

- 30 output range of the driver.

Thus, a given peak-to-peak voltage variation for the driver signal can be achieved using switching voltages with a voltage difference which is lower than the peak-to-peak variation. Using switching voltages with a lower voltage difference can be beneficial in

terms of reduced switching losses and reduced radiated emissions, as well as reducing the requirement for a significant output inductance.

5 **Figure 3** illustrates this principle. Figure 3 illustrates the switching waveforms at an output node of a switching driver according to one example and the resulting average voltage 301 over a duty cycle, i.e. the desired voltage of the drive signal output from the switching driver. It should be noted that figure 3 illustrates the switching waveforms for the driver signal generated at one driver output node, i.e. as would be applied to just one side of the load.

10

In this example, the drive signal may vary within a full output range between a peak low voltage VL and a peak high voltage VH. In this example, however, the switching driver is operable in different driver modes. In one mode of operation an output node of the switching driver may be switched between the peak high voltage VH and a first intermediate voltage V1. In another mode of operation, the output node may be switched between the first intermediate voltage V1 and a second intermediate voltage V2. In a further mode of operation, the output node may be switched between the second intermediate voltage V2 and the peak low voltage VL.

20

To generate a drive signal with a voltage in the range between the peak high voltage VH and the intermediate voltage V1, the output stage may operate in the mode that switches between VH and V1. For a drive voltage which is between the first intermediate voltage V1 and the second intermediate voltage, the output node may be switched between V1 and V2, and if the desired voltage for the drive signal is between V2 and the peak low voltage VL, the switching driver may operate in the mode to switch the voltage at the output node between V2 and the peak low voltage VL. In each case, the duty cycle is controlled appropriately to provide the desired average voltage.

30

Figure 3 illustrates that the full driver output range between VL and VH is provided by three different driver operating modes. However, in other embodiments, there may be a different number of driver operating modes across a full output range of the switching output stage, for instance in some embodiments there may be just two driver operating modes or there may be more than three driver operating modes. The voltage ranges for the driver operating modes, defined by the switching voltages, may be defined so that

the respective voltage ranges of the driver operating modes are contiguous and non-overlapping and collectively cover the whole of the full output range of the switching driver. In other embodiments however it may be advantageous to have some overlap between the output voltage ranges in the different driver operating modes. In some 5 embodiments the magnitude of the voltage range of each of the driver operating modes, i.e. the voltage difference between the relevant two switching voltages: VL and V2, V2 and V1, or V1 and VH; may be the same as one another.

It will be understood that the reference to a voltage range, for the switching driver in a 10 given operating mode, refers to the voltage of the drive signal at the driver output node (in terms of the average voltage over the course of a switching cycle) in that driver operating mode. The actual voltage that is applied across the load will, of course, depend on the voltage on the other side of the load, e.g. a defined DC voltage for a single-ended configuration or the voltage of a second drive signal on the other side of the load 15 generated by another driver for a BTL configuration. The output signal range, for the output signal applied across the load, may therefore be different to the driver voltage range. For instance with reference to figure 3, if a defined DC voltage Vdc on the other side of the load was set to be a midpoint voltage between V1 and V2, then the switched driver may operate in the mode with switching voltages V1 and V2 for low output signal 20 levels, up to a magnitude of  $(V1-V2)/2$  and may swap to switching voltages V1 and VH for higher positive output signal values (up to VH-Vdc) and swap to switching voltages VL and V2 for greater negative output signal values (down to VL-Vdc).

As used herein the term driver operating mode will thus refer to the operation of a driver 25 on one side of the load only, and the reference to a driver output voltage or output voltage range, or just voltage range, will refer to the voltage of a drive signal at the driver output node. For at least some BTL configurations, each side of the load may be seen as being driven by a respective driver, i.e. there are first and second drivers for driving both sides of the load. In some implementations, as will be discussed in more detail below, both of 30 the drivers of a BTL implementation may be separately operable in different modes, in which case an overall BTL operating mode may be defined by the individual operating modes of the individual drivers.

The switching driver may be configured to receive a high-side supply voltage and a low-side supply voltage, for instance a positive supply voltage and ground, which define an input voltage with a magnitude which is significantly lower than the full peak-to-peak output voltage range of the switching driver. Operating in the different driver operating

5 modes also means that the voltage difference between the switching voltages is significantly less than the full output range of the switching driver, even when operating to provide a drive signal voltage near the peak high output voltage  $VH$ . In this way, the maximum voltage stress across components of the switching driver can be kept to a magnitude which is lower than, and in some implementations significantly lower than,  
10 the peak-to-peak output voltage range of the switching driver. This can advantageously allow the use of components, e.g. transistors such as. FETs, with a voltage tolerance which may be significantly lower than the peak-to-peak output voltage of the driver circuit.

The switching driver may comprise a variable boost, or level-shifting circuit, such a  
15 charge pump, for providing some of the appropriate switching voltages for operation in the selected driver mode. The variable boost circuit may selectively positively boost (i.e. increase) the high-side input voltage and/or negatively boost (i.e. lower) the low-side input voltage to controllably vary at least one of the switching voltages for a mode of operation.

20 **Figure 4** illustrates one example of driving circuitry 400 with a variable boosting switching driver 401. In the example of figure 4 the switching driver 401 comprises a variable boost stage 402 and a switching output bridge stage 403. The variable boost stage 402 is configured to receive a high-side supply voltage  $VSUP$  and a low-side input supply  
25 voltage, which in this example is ground, which together define an input voltage  $Vin$ , i.e. as the voltage difference between the high- and low-side supplies. The switching output bridge stage 403 receives high-side and low-side-switching voltages  $VSH$  and  $VSL$  from the variable boost stage and switches a driver output node 404 between these two switching voltages with a controlled duty cycle to provide a desired average output  
30 voltage. In the example of figure 4 the high-side supply voltage  $VSUP$  for the switching driver 401 is derived from a power supply voltage  $VPS$ , which may, for instance be a battery voltage. In some implementations the power supply voltage  $VPS$ , may be regulated and/or level shifted to provide an appropriate supply voltage  $VSUP$  for the

switching driver, for instance there may be an initial boost stage 405 operable to provide a defined boost to the received power supply voltage VPS.

The variable boost stage is operable to controllably vary the switching voltages VSH and

5 VSL supplied to the output bridge stage 403 so as to provide the different driver modes of operation. In one example, in one mode of operation, the supply voltages to the switching driver 401, i.e. the voltages VSUP and ground (0V), may be used as the switching voltages VSH and VSL. In this mode of operation the supply voltages received by the switching driver 401 are thus used as the switching voltages and such a mode of

10 operation may be seen as an unboosted driver mode of operation as no voltage boosting is applied by the switching driver. It will be understood however, as described above, that at least one of the supply voltages received by the switching driver may itself have been boosted by an upstream component.

15 In one example, in another driver mode of operation, the supply voltage VSUP may be used as the low-side switching voltage VSL, with the variable boost stage being operable to generate a positively boosted higher voltage as the high-side switching voltage VSH. In one example, in another driver mode of operation, the low-side supply voltage, i.e. ground in this example, may be used as the high-side switching voltage VSH, with the

20 variable boost stage being operable to generate a negatively boosted lower voltage as the low-side switching voltage VSL.

In some applications the load 104 could be a reactive load, such as a piezoelectric transducer. Figure 4 also illustrates that there may be a series inductance 406 in the

25 load path, e.g. the load 104 may be connected in series with an inductor 406. Especially for piezoelectric transducers, the capacitive nature of such transducers means that it may generally be beneficial to include an inductor in series with the transducer. The inductor 406 may help suppress the switching ripple at the switching frequency, whilst allowing the current to flow for the signal band of interest, e.g. at audio or ultrasonic

30 frequencies.

**Figure 5** illustrates one example of the driver circuitry of figure 4 in more detail and similar components are identified by the same references.

Figure 5 illustrates that the output bridge stage 403 comprises two switching paths for selectively connecting the driver output node 404 to a first node N1 or a second node N2. Each switching path comprises a respective output switch SWO1 and SWO2. The variable boost stage 402 is configured to selectively control the voltages at the first and 5 second nodes N1 and N2 to enable the various modes of operation, and thus the first and second nodes N1 and N2 may be referred to as first and second switching voltage nodes.

The variable boost stage 402 comprises, in use, a capacitor 501 and network of switches 10 which are operable in a plurality of different switch states so as to provide different voltages at the switching voltage nodes N1 and N2. The network of switching paths is arranged such that the capacitor 501 can be charged to a desired voltage, which in this case is the input voltage. The switch network is also arranged so that the charged capacitor 501 can selectively provide voltage boosting to one of the first and second 15 switching voltages nodes in one of the driver modes of operation.

In the example of figure 5, the capacitor 501 is connected between the first and second variable boost nodes N1 and N2 and thus in parallel with the output bridge stage 403. This arrangement means that the voltage difference between the switching voltages 20 corresponds to the voltage on the capacitor 501.

In the example of figure 5, the network of switches is arranged to provide a first set of switching paths SW1A, SW1B and SW1C and a second set of switching paths SW2A, SW2B and SW2C. Switching paths SW1A and SW1B are provided to selectively 25 connect a node N3 to the high-side input voltage or the low-side input voltage respectively, i.e. VBST and ground in this example. The node N3 can thus be seen as a variable supply node or a supply select node. Switching path SW1C selectively connects the node N3 to the first variable boost node N1. Likewise, switching paths SW2A and SW2B selectively connect a node N4 to the high-side input voltage or the 30 low-side input voltage respectively and switching path SW1C selectively connects the node N4, which can be seen as a second variable supply, or supply select, node, to the second variable boost node N2. This arrangement means that a first electrode of the capacitor 501 can be selectively connected to either of the first or second input supplies.

Likewise a second electrode of the capacitor 501 can be selectively connected to either of the first or second input supplies.

It will be understood that the switching driver 401 may be implemented as an integrated circuit (IC), but in some embodiments the capacitor 501 may not be an integrated component and may be a separate component which is connected to the IC in use, i.e. the capacitor 501 may be off-chip. The capacitor 501 may therefore be connected between first and second capacitor nodes (not separately identified), which may be connected to suitable contacts of an IC for connection to an external capacitor.

10

In use, the driver circuit may be selectively operable in three different driver modes of operation, where the voltages at the switching voltage nodes N1 and N2, and hence the switching voltages for the output stage 403 vary in each mode.

15 In a first mode of operation the switching voltages may be +VSUP and ground. In a second mode of operation the switching voltages may be +2VSUP and +VSUP. In a third mode of operation the switching voltages may be ground and -VSUP. By swapping between the three modes of operation the switching driver circuit 400 can provide a peak-to-peak voltage range of 3VSUP in magnitude, from -VSUP to +2VSUP.

20

To provide the first mode of operation the switch network of the variable boost stage may be operable in a first switch state, in which switching paths SW1A and SW1C may be closed (with switching path SW1B open) to connect the high-side supply voltage VSUP to the first switching voltage node N1, and the switching paths SW2B and SW2C may be 25 closed (with switching path SW2A open) to connect the second switching voltage node N2 to the low-side supply voltage, i.e. ground in this example. This results in the switching voltage nodes N1 and N2 being connected to the respective high-side and low-side supply voltages. Whilst in this first state, the output bridge stage 403 can be controlled so that switching paths SWO1 and SWO2 alternately connect the driver output 30 node 404 to first and second switching voltage nodes with a duty cycle controlled to provide the desired average output voltage in the range 0V to +VSUP.

In this first state of the first mode of operation, the capacitor 501 is also connected between the high-side and low-side supply voltages and thus is charged to the input voltage  $V_{in}$  for the variable boost stage, i.e. to  $+VSUP$  in this example.

5 As, in this first state of the first mode, the switching voltage nodes N1 and N2 are connected to the respective high-side and low-side supplies, the load current can be supplied from the input supply to the variable boost stage.

In some implementations the switch network of the variable boost stage 402 may  
 10 additionally be selectively operable in an alternative switch state to provide the same switching voltages as the first mode. Switching paths SW2B and SW1C may be closed (with switching path SW2A open) to connect the second switching voltage node N2 to ground, as in the first state, but in this alternative switch state the switching path SW1C may be open. In this case the switching voltage node N1 is isolated from the supply  
 15 voltages (other than the path via the capacitor 501), but the voltage on (previously charged) capacitor 501 will maintain the voltage at the first switching voltage node N1 substantially equal to  $VSUP$ . In this alternative switch state, any load current can be supplied from the capacitor 501 (when the output path SWO1 is closed).

20 It will be noted that, in this first mode of operation the maximum voltage difference across any of switching paths, and thus any of the switches of the switch network, is substantially equal to the magnitude of the input voltage  $V_{in}$ , i.e. the voltage difference between the high-side and low-side supply voltages. The voltages at the switching voltage nodes N1 and N2 are  $+VSUP$  and ground respectively, whilst the voltages at node N3 and N4 are  
 25  $VSUP$  and ground respectively (at least in the first state – in the alternative state the voltage at node N3 may be floating or this node could be selectively connected to  $VSUP$  or ground by switching paths SW1a or SW1B respectively).

To provide the second mode of operation, switching path SW2A is closed (with switching  
 30 path SW2B open) to connect node N4 to the high-side supply voltage  $VSUP$  and switching path SW2C is closed to connect node N4 to the second switching voltage node N2. In this state, the second switching voltage node N2 is thus substantially equal to the high-side supply voltage  $+VSUP$ . Switching path SW1C is open, and the voltage of the capacitor 501, which is charged to the input voltage  $V_{in}$ , in this case equal to  $+VSUP$ ,

positively boosts the voltage at the first switching voltage node N1 to +2VSUP. This driver mode can thus be seen as a positive boosted mode of operation.

In this second switch state the voltage at the first switching voltage node N1 is boosted

5 to +2VSUP (i.e. boosted above the high-side supply voltage VSUP by the voltage Vin on the capacitor 501), and thus this node is disconnected from the supply voltages. It will be noted that if switch SW1C were not present, this disconnection could be achieved by opening both switching paths SW1A and SW1B. However, in that case the voltage at node N3 would be the same as that at the first switching voltage node N1, i.e. equal to

10 +2VSUP and thus the voltage across switch SW1B would be equal to +2VSUP, i.e. this switch would be subjected to a voltage stress of twice the input voltage. The inclusion of switching path SW1C reduces the voltage stress. Switching path SW1C is open, to disconnect the first switching voltage node N1 from the supply select node but the switching path SW1A may be closed (with switching path SW1B open) to connect node

15 N3 to the high-side supply voltage VSUP. This limits the voltage difference across the switch of the open switching path SW1C to a voltage of magnitude equal to the input voltage Vin (which in this case equals VSUP). Thus, the maximum voltage difference across any of the switching paths is again substantially equal to the magnitude of the input voltage.

20

Whilst the variable boost stage is in this second switch state, the output bridge stage 403 can be controlled so that the output switches of the switching paths SWO1 and SWO2 alternately connect the driver output node 404 to first and second switching voltage nodes with a duty cycle controlled to provide the desired average output voltage within

25 the range +VSUP to +2VSUP.

When operating in this second driver mode, the load current will be drawn from the capacitor 501. However, if the capacitance of the capacitor 501 is relatively large and the load for the output stage is a reactive load, the capacitor 501 can provide the charge

30 needed with just one charge pumping cycle. In particular, when the output bridge stage 403 drives an inductor 406 in the output path, this can enable lossless movement of charge between the load and the capacitor 501 for charge recovery.

It will be understood that for driving a transducer with a drive signal based on an input signal, such as an audio signal, the required drive voltage of the switched driver will vary with the input signal. High output voltages, such as enabled in the second driver mode of operation may only be required for relatively large amplitude drive signals and for only

- 5 part of the input signal cycle, when the input signal is near its peak. Thus, in normal operation, the second driver mode may be expected to be used for only parts of the signal cycle of the input signal, and for the switching driver circuit to be operating in the second driver mode of operation, e.g. in the range  $+VSUP$  to  $+2VSUP$ , the drive signal output from the switching driver will have passed through the voltage range of the first
- 10 mode, e.g.  $0V$  to  $+VSUP$ . Thus prior to operating in the second driver mode there will have been a period of operation in the first driver mode and thus the capacitor 501 will have been charged during such operation in the first driver mode.

The size of the capacitor 501 may thus be selected, based on the reactive load to be driven, such that a single charge of the capacitor provides sufficient charge for the driving of the reactive load over the course of a signal cycle for the input signal.

It will be noted that in the second switch state the second switching voltage node is connected to a voltage other than the second supply voltage (e.g. ground) and, in the example of figure 5, this is the first supply voltage  $VSUP$ . However, in some embodiments a different defined voltage, say  $0.5VSUP$  for example, could be derived and supplied to the second switching voltage node in this second stage, in which case the capacitor would boost the voltage at the first switching voltage node to  $1.5VSUP$ .

- 25 To provide the third mode of operation, the switch network of the variable boost stage may be operable in a third switch state, in which switching paths SW1B and SW1C are closed (with switching path SW1A open) to connect the first switching voltage node to the low-side supply voltage, i.e. ground. The first switching voltage node N1 is thus substantially equal to the low-side supply voltage, i.e. ground in this example. Switching path SW2C is open and the voltage of the capacitor 502, which is charged to the input voltage, i.e.  $VSUP$  in this case, negatively boosts, or lowers, the voltage at the second switching voltage node N2 to  $-VSUP$ . To control the voltage stress across the switch path SW2C, the switching path SW2B may be closed to cause the voltage at node N4 to be equal to ground.
- 30

Whilst the switch network of the variable boost stage is in this third switch state, the output bridge stage 403 can be controlled so that the output switches SWO1 and SWO2 alternately connect the driver output node 404 to first and second switching voltage nodes with a duty cycle controlled to provide the desired average output voltage within the range -VSUP to 0V.

It will thus be understood that the variable boost stage 402 is operable to controllably vary the voltages at the switching voltage nodes N1 and N2 to provide different switching voltages for the output stage 403 in the different driver modes of operation. One of switching voltages in the second and third modes of operation is selectively boosted by the voltage of the capacitor 501, which is charged during operation in the first mode by the input voltage, i.e. the voltage between the high-side supply voltage and the low-side supply voltage, VSUP and ground in this example. Each of the operating modes therefore involves switching voltages that differ from one another by a magnitude equal to the input voltage Vin for the variable boost stage, i.e. the difference between the high-side and low-side supply voltages. In the embodiment of figure 5 the capacitor is charged to the input voltage and as the capacitor is connected in parallel with the output stage 501, the switching voltages in a given mode of operation differ by an amount equal to the input voltage. In the embodiment of figure 5 one capacitor may be used to selectively provide both positive boosting or negative boosting as required.

It will also be clear that the maximum voltage stress across any of the individual switching paths can be limited to be substantially equal to the input voltage. Typically, each switching path may be implemented with a transistor, e.g. a MOSFET, as a switch and this means that a drain-source voltage tolerance of the transistor need only be sufficient to withstand a voltage of magnitude equal to the input voltage supply to the variable boost stage. Note that for correct operation of the transistor it may be beneficial to implement at least some of the transistor in doped wells which are driven with voltages based on the switching voltages, as will be discussed in more detail below.

The input voltage for the switching driver 401 may thus define the voltage tolerance required for the switches of the switch network of the variable boost stage and also define

the voltage range of the different operating modes, and hence the overall voltage range of the switching driver.

As noted above, in some examples, to provide an appropriate input voltage for the

5 variable boost stage 402, the driver circuitry 400 may comprise a first boost stage 405 for receiving a power supply voltage VPS and boosting the power supply voltage to provide at least one of the voltage supplies for the switching driver 401. In this example the first boost stage receives the power supply voltage VPS and boosts the power supply voltage VPS to provide the supply voltage VSUP. The first boost stage, if present, could

10 be any suitable DC-DC converter with a voltage boost and figure 5 illustrates that the first boost stage may comprise a boost converter with an inductor 502, control switches SW3A and SW3B and a reservoir capacitor 503 coupled to maintain the output voltage VBST.

15 In some examples the power supply voltage VPS could be a battery voltage and thus could be of the order of a few volts, say a voltage at or around 4.2V. In some examples this supply voltage could be boosted to a supply voltage VSUP of say 20V or so to provide the high-side supply to the switching driver 401. The low-side voltage may, in some examples, be ground, so the input voltage for the switching driver may be 20V.

20 For the example illustrated in the figure 5, the switching driver may thus be operable to generate a drive signal with a voltage range of 60V, from a voltage of -20V to a voltage of +40V, by selectively operating in one of the three different operating modes, a -20V to 0V mode, a 0V to +20V mode and a +20V to 40V mode.

25 The use of a first voltage defined boost stage to generate a first boosted voltage at a predetermined level which may then be selectively boosted by a variable boost stage represents one particular aspect of the present disclosure. In general, therefore, at least some embodiments relate to driver circuitry comprising a switching output stage 403 for driving an output node 404 between two switching voltages with a controlled duty cycle,

30 where the two switching voltages are selectively variable. A variable boost stage 402 may have first and second input nodes configured to receive a first high-side voltage and a first low-side voltage respectively and provide the switching voltages at first and second variable boost nodes. The variable boosting stage may be operably to selectively boost at least one of the first high-side voltage and the first low-side voltage to controllably vary

the switching voltages in different modes of operation. The driver includes a first defined boost stage 405 for a first defined boost stage configured to receive a supply voltage and boost the supply voltage to a defined voltage level to provide one of said first high-side voltage and first low-side voltage. The variable boost stage may be a switched capacitor

5 variable boost stage, e.g. charge pump, which can allow for charge recovery from the load.

As described above, each of the switches of the network of switches of the variable boost stage 402 and also the output switches of the output bridge stage 403 may be

10 implemented by a suitable transistor, e.g. a suitable MOSFET. **Figure 6** illustrates an example of a switch driver such as described with respect to figure 5, wherein each of the switches of the switching paths is implemented by a FET.

In one implementation, each of the FETs illustrated in figure 6 may be an NMOS FET

15 device. At least part of the NMOS devices may be formed in deep N-wells as will be understood by one skilled in the art. **Figure 7** illustrates schematically an example of two NMOS devices 701-1 and 701-2 formed on a substrate 702. Each of the NMOS devices comprises source and drain regions 703 and 704 formed in a bulk region 705, with a gate electrode 706 for controlling channel conduction. The bulk region is 705 is

20 disposed within a deep N-well 707. Isolation regions 708 isolate the N-wells from neighbouring devices.

In use, the substrate 702 and isolation regions 708 will typically be held at ground and the bulk 705 is typically coupled so as to be driven to the same voltage as the source

25 703. The deep N-wells 707 may be driven with a voltage that varies according to the signal range on the output to avoid P-well to deep N-well breakdown or unwanted forward biasing of the deep N-well to the substrate or P-well. By driving the voltages in this way, the transistor devices may be protected from high voltages.

30 **Figure 8** illustrates a table showing one example how the N-wells of the NMOS switches of the switching driver 401 of figure 6 may be driven when operating in the different modes. The table illustrated in figure 8 lists the switches of the switching driver for each of the operating modes, and in each case, the state of each of the switches, i.e. on, off or being operated with a controlled duty cycle (represented by DC), is indicated, along

with the respective source/bulk and drain voltages and the voltage to which the respective N-well may be driven.

In another implementation, the FETs illustrated in figure 6 may be a mixture of NMOS and PMOS devices. For example, the switches of switching paths SW1A, SW1C, SW01 and SW2A may be implemented as PMOS devices, whilst the switches of switching paths SW1B, SW02, SW2B and SW2C may be implemented as NMOS devices. As discussed, above the NMOS devices may be formed in deep N-wells. **Figure 9** illustrates schematically an example of an NMOS device 701 and a PMOS device 901 formed on a substrate 902. The NMOS device 701 may have the same structure as the NMOS device discussed with reference to figure 7. The PMOS device also comprises a source region 903 and drain region 904 in a bulk region 905, with a gate 906, but for the PMOS device, as the bulk region is N-type there is no need for any N well.

15 In use, the switching driver 401 could be operated in the same three modes as described above, and in operation the N-wells of the NMOS devices could be driven in the same way as illustrated in figure 8, with the bulk of the PMOS devices connected to be at the same voltage as the source.

20 **Figure 10** illustrates another example of a switching driver circuit 401 according to an embodiment. The embodiment of figure 10 includes an output bridge stage 403 with first and second output switches SW01 and SW02 connected between first and second switching voltage nodes N1 and N2, in a similar manner as described with respect to figure 5. The switching driver circuit 401 also includes a variable boost stage 402 for 25 controlling the voltages at the switching voltage nodes N1 and N2, which includes a first capacitor 1001 connected in parallel with the output bridge stage 403 between the first and second switching voltage nodes N1 and N2 and a network of switches, but in this example the variable boost stage also includes a second capacitor 1002.

30 The network of switches includes switching paths SW3A, SW3B and SW3C, which, together with the second capacitor 1002 effectively provide a first variable boost sub-stage. The second capacitor 1002 is coupled between variable boost nodes N1-1 and N2-1 of the first sub-stage, and switching paths SW3A and SW3B selectively connect variable boost nodes N1-1 and N2-1 to the high-side and low-side supply voltages

respectively, in this example VSUP and ground. In use, with switching paths SW3A and SW3B closed (and switching path SW3C open), the variable boost nodes N1-1 and N2-1 of the first sub-stage are substantially equal to the respective high-side and low-side supply voltages and the second capacitor 1002 is charged to a voltage equal to the input

5 voltage. Switching path SW3C selectively connects the high-side supply voltage to the second variable boost node N2-1. With switching path SW3C closed (and the switching paths SW3A and SW3B open), the variable boost node N2-1 of the first stage is driven to be substantially equal to the high-side supply voltage, i.e. +VSUP in this example, and the voltage at variable boost node N1-1 is positively boosted by the capacitor voltage,

10 i.e. to +2VSUP in this example.

Switching paths SW4A, SW4B and SW4C together with the first capacitor 1001, effectively provide a second variable boost sub-stage with the same general structure as the first sub-stage and which is operable in generally the same way. The second variable

15 boost sub-stage receives the voltages at nodes at the variable boost node N1-1 and N2-1 of the first boost sub-stage as respective high-side and low-side voltages. The second variable boost sub-stage is thus operable to either provide these voltages received from the first boost sub-stage as switching voltages to the switching voltage nodes N1 and N2, or to provide the voltage from node N1-1 to the second switching voltage node N2,

20 with the capacitor 1001 providing further positive boosting for the voltage at the first switching voltage node N1.

The switching driver of figure 10 is thus operable in three different operating modes, a first (no boosting) mode, a second (single) boosted mode and third (double) boosted.

25 For the example of figure 10 where the high-side and low-side voltage inputs are +VSUP and ground respectively, this means the first mode will have switching voltages of 0V and +VSUP, the second mode will have switching voltages of +VSUP and +2VSUP and the third mode will have switching voltages of +2VSUP and +3VSUP.

30 In the first mode of operation, switching paths SW3A, SW3B, SW4A and SW4B may all be closed so as to charge both the first and second capacitors. This means that the input supplies are connected to the switching voltage nodes and any load current can be supplied from the input supplies. In an alternative state of operation, the switches SW3A

and SW3B could be opened so that the capacitors 1001 and 1002 provide the load current.

In operation in the second mode, the boosting could be provided by the first boost sub-  
 5 stage, i.e. with switching path SW3C closed (and SW3A and SW3B open) and the second boost sub-stage may be operated to pass through the voltages without any boosting, i.e. with switching paths SW4A and SW4B closed (and SW4C open). Alternatively, the first boost sub-stage may effectively be bypassed, with switching path SW3A closed (and SW3C and SW3B open) and the boosting provided by the second  
 10 boost sub-stage with switching path SW4C closed (and SW4A and SW4B open).

The switching driver 401 illustrated in figure 10 is thus also operable in three different driver operating modes, wherein the output range of the switching driver in each mode is equal to the input voltage for the switching driver 401 and the full output range of the  
 15 driver is thus equal to three times the input voltage. The maximum voltage stress across any of the switching paths is limited to magnitude of the input voltage and thus for an input voltage equal to 20V, a drain-source voltage tolerance of 20V would be sufficient for the transistors of the switching paths.

20 However, the peak high switching voltage for the switching driver of figure 10 is, in this example, equal to +3VSUP compared to a maximum voltage of +2VSUP in the example of figure 5. In some applications this may require the transistor devices to have a sufficiently large drain to substrate breakdown voltage.

25 The switching driver illustrated in figure 10 may be implemented by NFET devices for each of the switching paths. **Figure 11** illustrates schematically one example of suitable NFET devices 1101-1 and 1101-2. The devices are formed on a substrate 1102 and comprise source and drain regions 1103 and 1104, bulk region 1105 and gate 1106. In this example, however, the source region 1103 is formed within the bulk region 1105  
 30 within an N-well 1107, but the drain region 1104 is formed within the N-well.

An isolation region 1108 may isolate the devices from one another and, in use, the isolation region 1108 and substrate 1102 may be grounded. In use, the N-well 1107 may be driven to a voltage that is the same as the drain voltage.

Figure 10 illustrates an example, where there are two boosting sub-stages for providing selective positive boosting, but it will be understood that other arrangements are possible, for instance there may be more selective boosting sub-stages to allow more

5 output voltage ranges and at least some of the multiple boosting sub-stages could provide negative boosting.

In general, therefore embodiments provide a switching driver for generating a drive signal for driving a load, where the switching driver is operable in a plurality of different modes,

10 where each of the modes involves switching between different switching voltages so that the output range of the driver varies in the different modes, and where the output range for each mode corresponds to only a subset of the full output range of the driver.

In some examples the switching driver may be arranged to drive a transducer load in a

15 single-ended configuration. Referring back to figure 4, the switching driver 401 may therefore be arranged to provide a first driving signal at the driver output node 404 for driving the load 104, where the other side of the load is held at a DC voltage. The DC voltage could, for example, be a voltage which is at a midpoint of the full operating range of the switching driver. For instance, for the example discussed with reference to 20 figure 5, where the switching driver is operable between a peak high-side voltage of +2VSUP in the second mode and a peak low-side voltage of -VBST in the third mode, the midpoint voltage is +VSUP/2. In some examples the level of the DC voltage at the other side of the load may be varied in use, as will be described in more detail below.

25 In some implementations, however, a driver circuit may comprise two switching drivers arranged to drive a load in a BTL configuration. **Figure 12** illustrates a driving circuit 1200 according to an embodiment with respective first and second switching drivers 401-1 and 401-2 for driving the load in a BTL arrangement. Each of the switching drivers 401-1 and 401-2 may be a switching driver according to any of the embodiments 30 described herein. In the example of figure 12 the two switching drivers 401-1 and 401-2 are provided with the same high-side and low-side voltage inputs as one another, in this example VBST and ground.

Figure 12 illustrates that the switching of each switching driver 402-1 and 402-2 may be controlled by a controller 1201. The controller 1201 receives the input signal Sin and based on the input signal Sin, determine the appropriate driver mode of operation for each of the switching drivers 401-1 and 401-2 and generate switching control signals for 5 controlling the relevant switches of the network of switches so as to set an appropriate switch state to select the mode of operation. The controller also generate the relevant switching control signals for the output switch of the output stage of each of the switching drivers 401-1 and 401-2 to alternate between the relevant switching voltages with an appropriate duty cycle so as to provide the desired voltage at each driver output node 10 and hence the desired differential voltage across the load.

The controller 1201 thus controls the driver mode of operation of each of the switching drivers 401-1 and 401-2 so as to provide a desired output voltage across the load. The controller 1202 controls the individual driver modes of the drivers 401-1 and 401-2 to 15 provide an appropriate overall BTL operating mode of the driver circuit to provide the desired output signal across the load.

For instance, consider the example where each of the switching drivers 401-1 and 401-2 is a switching driver as discussed with reference to figure 5, and thus is operable in a 20 first driver mode with a driver output voltage in the range 0V to +VSUP, a second driver mode with a driver output voltage in the range +VSUP to +2VSUP or a third driver mode with a driver output voltage in the range -VSUP to 0V. The first mode can be seen as providing a mid-range drive voltage, with the second and third modes provides high-range (more positive than the mid-range) and low-range (more negative than the mid-range) driver voltages respectively. For the example of the switched driver of figure 5, the first mode can be seen as an unboosted mode of operation of the driver as the 25 voltage supplies received by the switching driver are used as the switching voltages. The second mode can be seen as a positive boosted mode and the third mode can be seen as a negative boosted mode.

30

To generate a differential voltage across the load with a magnitude in the range of 0V to +VSUP, each of the drivers 401-1 and 401-2 may be operated in the first driver mode, i.e. with a driver voltage range between 0V and +VSUP. In effect the first switching driver

401-1 generates a first drive signal in the range of 0V to +VSUP and the second switching driver 401-2 generates a second drive signal in the range of 0V to +VSUP.

Assuming that a positive voltage across the load corresponds to the voltage at the output

- 5 node of first switching driver 401-1 being more positive than the voltage at the output node of the second switching driver 401-2, then to provide a positive voltage, the duty cycle for the first switching driver 401-1 (in terms of proportion of time spent at the high-side switching voltage) should be greater than that for the second switching driver 401-2. The differential drive signal across the load may thus be varied between +VSUP (with
- 10 the first drive signal at a voltage +VSUP and the second drive signal at a voltage of 0V) and -VSUP (with the first drive signal at a voltage +VSUP and the second drive signal at a voltage of 0V)

In some applications the controller could control the two switching drivers 401-1 and

- 15 401-2 so that the drivers switch synchronously in antiphase, i.e. such that the switching drivers switch between the switching voltages at the same time as one another so that the output node of the first driver 401-1 is connected to its respective high-side switching voltage whilst the output node of the second driver 401-2 is connected to its respective low-side switching voltage and vice-versa. In some implementations, however, it may
- 20 be beneficial, at least in some use cases, for the switching of the two output stages of the switching drivers to be asynchronous, i.e. such that the switching drivers 401-1 and 401-2 may switch between their respective switching voltages at different times to one another such both switching drivers may be connected to their respective high-side or low-side switching voltage at the same time for at least part of the duty cycle.

25

To provide a differential voltage across the load of a greater magnitude, the switching drivers on the opposite sides of the load may be operated in different driver modes from one another. For instance, a differential voltage across the load with a magnitude in the range of VSUP to 3VSUP could be achieved by operating the switching driver on one side of the load in the second driver mode, to provide a driver voltage in the range +VSUP to +2VSUP whilst the switching driver on the other side of the load is operated in the third driver mode, to provide a driver voltage in the range 0V to -VSUP.

For instance, a positive differential voltage across the load could vary from +VSUP (with the voltage of the first driver signal from driver 401-1 at a voltage equal to +VSUP and the voltage of the second driver signal from driver 401-2 at 0V), to +3VSUP (with the voltage of the first driver signal from driver 401-1 at a voltage equal to +2VSUP and the 5 voltage of the second driver signal from driver 401-2 equal to -VSUP).

For a relatively low magnitude differential voltage across the load, i.e. a differential signal in the range -VSUP to +VSUP, the controller 1201 could control the switching drivers 401-1 and 401-2 to each operate in the first driver mode (i.e. each generating a mid- 10 range voltage). This can be seen as a first, low signal level BTL mode of operation of the driver circuit. For higher magnitudes of differential voltage across the load, i.e. a magnitude greater than VSUP (up to the maximum magnitude of 3VSUP), the controller 1201 could control one of the drivers 401-1 and 401-2 to operate in the second mode of operation (to provide a more positive drive voltage) and the other to operate in the third 15 mode of operation (with a more negative drive voltage). Operating in this way, with one driver operating in the second mode and one driver operating in the third mode can be seen as a high-signal level BTL mode of the driver circuit. Which of the drivers 401-1 and 401-2 operates in the second mode and which in the third will be controlled depending upon whether a positive or negative differential voltage is required across the 20 load.

In some implementations the controller 1201 could be implemented to swap between just these BTL modes of operation, i.e. to operate in the low-signal BTL mode for differential signal magnitudes below VSUP and then swap to the relevant positive or 25 negative high-signal BTL mode as appropriate when the differential signal magnitude increases.

However, it can, in some implementations, be beneficial to also operate with one of the switching drivers in the first driver mode of operation (to provide a mid-range drive 30 voltage) whilst operating the other switching driver in one of the second or third modes of operation.

For example, the first switching driver 401-1 could be operated in the second driver mode to switch between voltages in the range of +VSUP to +2VSUP, whilst the switching driver

401-2 is operated in the first mode to switch between 0V and +VSUP. Thus, the first switching driver 401-1 generates a first drive signal with a voltage in the range of +VSUP to +2VSUP whilst the second switching driver generates a second drive signal in the range of 0V to +VSUP. This could allow a differential voltage in the range of 0V (with

5 the first drive voltage from driver 401-1 at +VSUP and the second drive voltage from driver 401-2 at +VSUP) to +2VSUP (with the first drive voltage from driver 401-1 at +2VSUP and the second drive voltage from driver 401-2 at 0V).

Alternatively, the first switching driver 401-1 could be operated in the first driver mode, 10 and switched between 0V and +VSUP, whilst the second switching driver 401-2 is operated in the third mode to switch between -VSUP and 0V. Thus, the first switching driver 401-1 generates a first drive signal with a voltage in the range of 0V to +VSUP whilst the second switching driver 401-2 generates a second drive signal with a voltage in the range -VSUP and 0V, to apply a differential signal across the load in the range of 15 +VBST to +2VBST. Again, this could allow a differential voltage in the range of 0V (with the first drive voltage from driver 401-1 at 0V and the second drive voltage from driver 401-2 at 0V) to +2VSUP (with the first drive voltage from driver 401-1 at +VSUP and the second drive voltage from driver 401-2 at -VSUP).

20 Operating the switching drivers 401-1 and 401-2 with one driver operating in the first driver mode (to provide a mid-range voltage) whilst operating the other switching driver in one of the second or third driver modes, can thus be seen as an intermediate signal-BTL mode of operation.

25 Table 1 below summarises one example of how different ranges of differential output voltages  $V_{diff}$  across the load may be generated by voltages  $V_x$  at the outputs of the first and second switching drivers 401-1 and 401-2 where the high-side voltage input, i.e. VSUP, is 20V and the low-side voltage input is ground.

<b>V<sub>diff</sub></b>	<b>V<sub>x</sub> 401-1</b>	<b>V<sub>x</sub> 401-2</b>
0-20V BTL low-signal mode	0 to 20V (first driver mode)	0 to 20V (first driver mode)
20-40V BTL intermediate signal mode	20 to 40V (second driver mode)	0 to 20V (first driver mode)
40-60V BTL high signal mode	20 to 40V (first driver mode)	-20 to 0V (third driver mode)

Table 1

5 Differential voltages of the opposite polarity across the load can be achieved in a similar manner by swapping the relevant driver modes of operation of the first and second switching drivers 401-1 and 401-2.

10 It will thus be clear that, in this example a differential driving signal can be applied across the load which can vary in the range from +3VSUP to -3VSUP, i.e. a peak-to-peak differential voltage range equal in magnitude to six times the input voltage for the switching drivers 401-1 and 401-2. As discussed above, the switching drivers 401-1 and 401-2 may be implemented so the maximum voltage stress across the switching paths is equal to the input voltage, i.e. VSUP, and thus the switching drivers may only require a voltage tolerance which is of the order of 1/6<sup>th</sup> of the peak-to-peak differential output of 15 the driver circuitry 1200. Thus, the driver circuitry 1200 may utilize transistors, for example MOS transistors, having less breakdown voltage than the peak-to-peak differential output voltage, for example approximately 1/6th the breakdown voltage of the peak-to-peak differential output voltage of the driver circuitry.

20 Table 1 illustrates just one example, however, and the controller may control the respective driver modes of operation according to different differential output ranges. The controller may operate the first and second switching drivers in a given differential or BTL mode of operation, where each differential or BTL mode of operation involves a different combination of individual driver modes of the first and second switching drivers.

25

Driver circuitry which thus drives a load with two switching drivers in a BTL configuration, where the switching voltages on both sides of the load can be separately varied

represents another aspect of this disclosure. Thus, in general, at least some embodiments relate to a driver circuit for driving a transducer based on an input signal comprising first and second switching drivers configured to drive the transducer in a bridge-tied-load configuration; wherein each of the first and second switching drivers

5 comprise an output stage for controllably switching a driver output node between first and second switching voltages with a controlled duty cycle. Each of the first and second switching drivers is operable in a plurality of driver modes, wherein the first and second switching voltages are different in each of said modes. A controller controls the driver mode of operation and duty cycle for each of the first and second switching drivers, such

10 that the first and second switching drivers may be operable in different driver modes from one another with different switching voltages.

The controller 1201 may thus control the driver mode of operation of each of the switching drivers 401-1 and 401-2, and the respective duty cycle, so as to provide a

15 desired differential drive voltage based on the input signal  $S_{in}$  and may vary the driver mode of operation of the switching drivers as the input signal varies.

Thus, for example, consider the operation illustrated in table 1 above, and consider that the required differential output voltage, based on the input signal is 0V. The controller

20 1201 may operate both switching drivers in the first driver mode (0 to 20V), i.e. operate in the low-signal level BTL mode, and may control the switch drivers with equal duty cycles. If the value of the input signal then rises over time, the controller could increase the duty cycle of the first switching driver/reduce the duty cycle of the second switching driver to provide the increased differential output voltage. If the required voltage for the

25 drive signal continues to rise, in particular to a voltage of greater than 20V, the controller could then swap the mode of operation of the first switching driver to the second driver mode of operation (20 to 40V) with an appropriate duty cycle.

In theory, during the operation in the first driver mode, the duty cycle of the first switching

30 driver 401-1 could be increased to 100% whilst the duty cycle of the second switching driver 401-1 was decreased to 0% to provide a differential output voltage of 20V. In practice, however, limits on the clock speeds and the speed of the response of the transistors means that duty cycles of 100% and 0% may not be practically realisable. Thus, in some implementations it may not be practical to generate a differential output

voltage of 20V in the low signal level BTL mode, with the first and second switching drivers 401-1 and 401-2 each operating in the first driver mode with switching voltages of 0V to 20V.

5    However, a differential voltage of 20V could be achieved by operating in the intermediate signal level BTL mode, with one switching driver operating in the first driver mode and the other operating in one of the second or third driver modes. Thus, the first switching driver could be operated in the second driver mode (in this example with switching voltages of 20V and 40V) to generate a first drive signal with a voltage greater than 20V,  
 10   say 22V for example, whilst the second switching driver 401-2 is operated in the first mode (with switching voltages of 0V and 20V) to provide a voltage greater than 0V, say 2V, so that the differential voltage between the first and second driving signals corresponds to the required differential output. This allows the desired output signal to be generated whilst operating both switching drivers with valid duty cycles.

15   In some cases, the duty cycle for a switching driver could be validly varied within certain limits, e.g. between lower and upper or minimum and maximum duty cycle limits, say between 5% and 95% or between 10% and 90% in some implementations, although different may be used in other implementations (which may be, but need not be,  
 20   symmetrical about 50%). In use, the controller 1201 may operate each of the switching drivers 401-1 and 401-2 in a given mode of operation and controllably vary the duty cycle with input signal between these limits, but once the relevant limit for at least one of the switching drivers is reached the controller 1201 may swap the driver mode of operation of one of the switching drivers at the duty cycle limit, and controllably vary the duty cycles  
 25   of both drivers, based on the new operating mode, to provide an equivalent differential voltage. This can, however, vary the common-mode voltage of the first and second drive signals applied to the load in the different BTL modes of operation.

30   Table 2 below illustrates one example of how various different differential voltages could be achieved, for the example where switching drivers are operable in a first driver mode with switching voltages of 0V and 20V, a second driver mode with switching voltages of 20V and 40V and a third driver mode with switching voltages of 0V and -20V. Table 2 illustrates the differential output voltage  $V_{diff}$ , and for each of the first and second switching drivers 401-1 and 401-2, the respective drive voltage  $V_x$  (i.e. the average

voltage at the driver output over the duty cycle), the switching voltages SW and the duty cycle DC (in terms of proportion of time spent at the high-side switching voltage). Table 2 also illustrates the resulting common-mode voltage VCM of the first and second driver signals. Note that the reference to the common-mode voltage or common-mode voltage

5 component refers to the average common-mode voltage component of the drive signals, i.e. determined over a full switching cycle. It will be understood that during the cycle, there may be some common-mode ripple depending on the timing of switching between the switching voltages on either side of the load.

10

Vdiff	First Driver 401-1			Second driver 401-2			VCM
	Vx1	SVs	DC	Vx2	SVs	DC	
12	16	20/0	80%	4	20/0	20%	10
14	17	20/0	85%	3	20/0	15%	10
16	18	20/0	90%	2	20/0	10%	10
16	22	40/20	10%	6	20/0	30%	14
18	23	40/20	15%	5	20/0	25%	14
20	24	40/20	20%	4	20/0	20%	14
22	25	40/20	25%	3	20/0	15%	14
24	26	40/20	30%	2	20/0	10%	14
24	22	40/20	10%	-2	0/-20	90%	10

Table 2

In the example of figure 2, the duty cycle of each of the switching drivers may be controllably varied with minimum and maximum duty cycle limits of 10% and 90%. It can  
15 be seen that, in this example, a differential voltage of up to 16V can be generated by operating in the low-signal level BTL mode, i.e. with both switching drivers operating in the first driver mode with valid duty cycles in the range of 10% to 90%. In this example the duty cycles of the switching drivers, in the low-signal level BTL mode, are controlled to vary equally and oppositely about a duty cycle of 50% and thus the common mode  
20 voltage is equal to 10V.

At the differential output of 16V the duty cycle of the first switching driver 401-1 is at the maximum duty cycle limit of 90% and cannot be increased further, and likewise the

second switching driver 401-2 is at the minimum duty cycle limit of 10%. When the duty cycle limit is reached, the controller transitions the first switching driver to operate in the second driver mode, with switching voltages of 20V and 40V, and sets the duty cycle for the first switching driver to the minimum duty cycle limit. At the minimum valid duty cycle,

- 5 in this example 10%, the voltage of the first driver signal is thus 22V. To provide the correct differential voltage of 16V, the operation of the second switching driver is maintained in the first driver mode, but the duty-cycle is varied to provide a second drive signal with a voltage of 6V, which, in this example, involves operating with a duty cycle of 30%. The controller thus effectively transitions from the low signal level BTL mode of
- 10 operation to the intermediate signal level BTL mode of operation by transitioning the driver mode of operation on one side of the load (whilst maintaining the driver mode on the other side of the load) and maintains the same differential voltage across the load when transitioning. This does however result in the common-mode component of the first and second drive signals increasing to 14V.

15

If the required differential output  $V_{diff}$  increases further, the duty cycle of the first switching driver 401-1 may be increased, with the duty cycle of the second switching driver 401-2 being correspondingly reduced, i.e. the duty cycles may be varied equally and oppositely, which maintains the common-mode voltage at a substantially constant value (14V in this example) when operating in the intermediate signal level BTL mode. The duty cycles may be varied until the duty cycle of the second switching driver 401-2 reaches the minimum limit of 10%, which in this example occurs for the differential output voltage of 24V.

- 25 At this point, the mode of operation of the second switching driver 401-2 may be changed to the third driver mode, with switching voltages of -20V and 0V, and the duty cycle of second switching driver set to the maximum duty cycle limit, which in this example is 90% which provides a driver voltage  $V_x$  from the second driver of -2V. To provide the desired differential voltage of 24V, first switching driver 401-1 may continue to operate
- 30 in the second mode and the duty cycle controlled to provide a voltage for the first drive signal of 22V, which in this case corresponds to the minimum duty cycle of 10%. Thus the controller 1201 effectively transitions to the high-signal level BTL mode of operation. This provides the desired differential output and also returns the common-mode voltage to 10V.

Further increases in the differential output voltage  $V_{out}$  can then be achieved by continuing to operate in the high-signal level BTL mode, with the first switching driver 401-1 in the second driver mode and the second switching driver 401-2 in the third driver mode, and increasing the duty cycle of the first switching driver whilst decreasing the duty cycle of the second switching driver. Applying equal and opposite changes to the duty cycle will maintain the common-mode voltage at 10V.

It should be understood that the duty cycle limits of 10% and 90% are just an example and other limits could be implemented.

Operating in this way, with a variation or jump of the common-mode voltage, which may be referred to as operating with a bumped common-mode, thus allows voltages around 20V (in this example) to be achieved with valid duty cycles.

15

**Figure 13** illustrates some example voltage waveforms to illustrate this principle. Figure 13 illustrates, in the second and third waveforms from the top, the voltages  $V_{x1}$  and  $V_{x2}$  of the drive signal at the respective driver output nodes (in terms of the average voltage over the course of a duty cycle). Figure 13 also illustrates, in the top waveform, the resultant differential voltage  $V_{diff}$  across the load. The lower two waveforms illustrate the switching waveforms at the respective driver output node, for parts of the waveforms illustrated in the top plots, and illustrate how the switching voltages and duty cycles may vary across a mode transition.

25 In this example, each of the switching drivers 401-1 and 401-2 is operable in three modes, similar to those discussed above with reference to figure 3. Figure 13 illustrates the example where the differential output voltage, which depends on the relevant input signal, varies positively and then negatively with a relatively high amplitude.

30 Figure 13 illustrates that initially the required differential voltage across the load is zero, and both the switching drivers operate to provide the same quiescent voltage level, which in this case is a midpoint voltage between  $V_1$  and  $V_2$ . Both switching drivers 401-1 and 401-2 may thus operate in the first mode switching between switching voltages  $V_1$  and  $V_2$ , i.e. the low-signal BTL mode, and both switching drivers may each initially operate

with a duty cycle of 50%. As the required differential voltage increases, the duty cycle of the first switching driver 401-1 is increased, with an equal and opposite change to the duty cycle of the second switching driver 401-2, so the driver voltages  $Vx1$  and  $Vx2$  vary equally and oppositely.

5

As the required differential voltage  $Vdiff$  increases, the first switching driver 401-1 transitions to operating in the second mode, with switching voltages of  $VH$  and  $V1$ . As discussed above, however, it may not practically be possible for the switching driver to operate with a duty cycle that goes as high as 100% or a low as 0%. Thus the duty-cycle 10 of the first switching driver will go from a duty cycle less than 100% in the first mode to a duty-cycle greater than 0% in the second mode. As such the average of the drive voltage  $Vx1$  (over the course of the switching cycle) jumps from a value below  $V1$  to a value above  $V1$ . The same jump in voltage is thus applied to the driver voltage  $Vx2$  of the second switching driver 401-2 to maintain the correct differential voltage. The second 15 switching driver 401-2 thus continues to operate in the first mode and the system operates in the intermediate signal level BTL mode.

As the required differential voltage  $Vdiff$  increases further, the second switching driver transitions to the third mode, with switching voltages of  $V2$  and  $VL$ , to provide the high-20 signal level BTL mode. Again, the practical duty cycle limits result in a jump in the voltage  $Vx2$  across the transition, and thus a corresponding voltage jump is applied to  $Vx1$  to maintain the correct differential voltage  $Vdiff$ .

Figure 13 also illustrates that similar jumps may apply when transitioning back to the 25 intermediate signal level BTL mode and then the low-signal level BTL mode and also for the negative part of the cycle.

Figure 13 also illustrates examples of the switching waveforms across two of the mode transitions. In the first case, both switching drivers are initially operating in the first mode 30 with switching voltages  $V1$  and  $V2$ , and then at a time illustrated by arrow 1301, the second switching driver transitions to the first mode, with switching voltage  $VH$  and  $V1$ , i.e. to the BTL intermediate signal level mode for a negative differential voltage. Just before the transition the output node of the second switching driver 401-2 is switching between the switch voltage  $V1$  and  $V2$  with a duty cycle at a defined duty cycle maximum.

After the transition, illustrated by arrow 1301, the output node of the second switching driver switches between the voltages VH and V1, with a minimum duty cycle. The output node of the first switching driver 401-1 continues to switch between the voltages V1 and V2, but the duty cycle is increased across the transition 1301.

5

The second case illustrates the transition to the high-signal level BTL mode of operation, where the first switching driver transitions 1302 to the third driver mode with switching voltage V2 and VL and an increase of duty cycle from minimum to maximum and the second switching driver continues to switch between the voltages VH and V1 but with a 10 reduce duty cycle.

15 **Figure 14** illustrates how the duty cycle of the switching drivers may vary on each side of the load to provide a differential output waveform such as illustrated in the top plot figure 13, in this example where the maximum and minimum duty cycles are 75% and 25% respectively.

It will also be noted that, as in these example, where the high switching voltage in the first driver mode is the low switching voltage in the second driver mode, and the difference between the switching voltages are the same in each of the modes, then 20 changing from the first driver mode to the second driver mode can be considered mathematically the same as adding an additional 100% to the duty cycle in the first mode. In other words a change from 90% duty cycle in the first driver mode to 10% duty cycle in the second driver mode, can be considered to mathematically the same as an increase from 90% to 110% for the switching voltages of the first driver mode. This change can 25 thus be seen as increase in duty cycle of 20%, and thus to maintain the same differential voltage on such a mode transition, an equivalent change in duty cycle is made to the other driver, i.e. an increase in duty cycle from 10% to 30%. In other words, the magnitude of a change in duty cycle applied to both drivers equals 100%, that is if the duty cycle of the first driver is reduced from 90% to 10% on a mode change, which 30 represents a change in duty cycle of 80%, the corresponding change in duty cycle applied to the second driver is 20%.

It should also be noted that defined maximum and minimum limits for the purposes of a mode a mode transition need not be the same as a practically achievable duty cycle limit.

For instance, it may in some cases be advantageous to swap between a maximum duty cycle of 75% and a minimum duty cycle of 25%. This particular combination means that the change in duty cycle on each side of the load over a transition is 50% and on each transition the duty cycle on one side of the load transitions from 75% to 25% and the 5 duty cycle in the other side of the load transitions from 25% to 75%. This can be advantageous in terms of minimising discontinuities on mode transition.

The controller can therefore be seen as implementing three BTL modes of operation, (i) a low-signal level BTL mode, with both drivers operating in the first driver mode to provide 10 a mid-range voltage; (ii) an intermediate signal level BTL mode with one driver operating in the first driver mode and the other driver operating in the second or third driver mode to provide a high (relatively positive) or low (relatively negative) range voltage; and (iii) a high-signal level BTL mode with one driver operating in the second driver mode to provide a high (positive) voltage range and the other driver operating in third driver mode 15 to provide a low (negative) voltage range. The controller may operate in a given mode and controllably vary the duty cycle of both drivers within defined maximum and minimum limits of duty cycle. The controller may control the duty cycles to vary with input signal level within the limits, so that a common-mode component does not substantially vary with signal level in a given operating mode. If required, the controller may transition 20 between modes, where each transition involves changing the driver mode, i.e. the switching voltages, on one side of the load only. This, if the input signal changes increase say the controller may transition from the low-signal level BTL mode to the intermediate signal level mode by changing the switching voltages one side of the load and then, if the input signal continues to increase, later transition to the high-signal level 25 mode by changing the driver mode on the other side of the load.

The controller may be configured so that the common-mode component of the first and second driver signals is substantially the same in the low-signal level BTL mode and the high-signal level BTL mode, which may correspond to a midpoint voltage between the 30 switching voltages used in the first driver mode. The common-mode component may be different when operating in the intermediate signal level BTL mode.

In general therefore, the controller may be configured to implement a transition in mode of one of the switching drivers, from the present driver mode to a new driver mode, by

initially controlling the switching driver (undergoing the mode change) to operate in the current driver mode with a first duty cycle, whilst controlling the other switching driver with a second duty cycle. The controller may then transition the relevant switching to operate in the new driver mode (with different switching voltages) with a modified duty

5 cycle and may also modify the duty of the other switching driver to maintain the same differential voltage across the transducer. The controller may, in particular, be configured to transition between different driver modes of operation when the duty cycle of at least one of the first and second switching drivers reaches a maximum or minimum duty cycle limit. The controller may implement the transition by changing the driver mode of one of

10 the first and second switching drivers at said maximum or minimum limit of duty cycle and vary the duty cycle of that one of the first and second switching drivers to the other limit of duty cycle (i.e. from maximum to minimum or vice versa) whilst maintaining the driver mode of the other of the first and second switching drivers and applying a variation in duty cycle to maintain a magnitude of a differential component of the first and second

15 driver signal.

Note, similar principles could be applied to a driving circuit for driving a load in a single ended configuration, if the DC voltage on the other side of the load could be controllably varied, so to avoid discontinuous in the drive signal applied to the load due to switching

20 driver being unable to achieve a duty cycle (i.e. modulation index) of 100% or 0%.

For example, consider that a switching driver is configured to drive one side of a load in a single ended configuration and is operable in a first mode with switching voltages 0V and 20V, and a second mode with switching voltages of 20V and 40V. Whilst operating

25 in the first mode, the voltage on the other side of the load may be held at a first DC value, say 2V purely as an example. The duty cycle of the switching driver may be controllably varied within a range up to a defined limit, which could, for example, be a duty cycle or modulation index of 90%, which could lead to a voltage for the drive signal from the switching driver of 18V, leading a voltage of 16V across the load. To transition between

30 modes of operation, to allow for higher voltages to be applied, the switching driver may initially be operated in the first mode at a duty cycle of 90%, and then switched to operate in the second mode with a duty cycle of 10%. At the same time, the DC voltage on the other side of the load may be increased to 6V. **Figure 15** illustrates the relevant switching waveform 1301 for the output node of the switching driver and the voltage 1302

on the other side of the load for such a transition and the load current. It will be seen that by changing the duty cycle or modulation index from 90% to 10% and also changing the DC voltage, the volt-second balance is maintained as well as the differential voltage.

5 In a bridge-tied-load configuration, where both sides of the load are driven by a switching driver, second order effects can appear. The inductor current matches the output-based duty cycle and discontinuity of charge transfer can occur.

10 **Figure 16** illustrates some example waveforms for driver circuitry comprising first and second switching drivers according to embodiments of the disclosure and illustrates a mode transition for the switching voltages for the first switching driver. Figure 16 illustrates two sets of waveforms, (a) and (b) in each case showing the differential output voltage  $V_{diff}$ , the first and second output currents 1601 and 1602 for the first and second switching drivers respectively and the voltages 1603 and 1604 at the output nodes for 15 the first and second switching drivers respectively during a mode transition.

20 In the top set of waveforms (a), it can be seen that the first switching driver is initially operating with the same switching voltages as the second switching driver. It can be seen that the duty cycle for the first switching driver is relatively high, i.e. the relevant drive voltage is near the maximum for the driver mode of operation. The driver mode of operation for the first switching driver then changes, and it starts switching between the previous high voltage and a higher boosted voltage, but now with a relatively short duty cycle. It can be seen that, in this example, the change to the switching voltages and 25 resultant change in duty cycle results in a disturbance in the current waveforms, with a consequent disturbance in the output voltage.

30 In some implementations this can be mitigated by a controlled variation in the switching timing. The lower set of waveforms (b) show a similar transition, but the timing of switching to the high-side voltage in the second mode is controlled to occur at a suitable point which does not result in any significant disturbance in the current waveforms.

At the point of a mode transition the switching voltages on one side of the load vary and there is a change in duty cycle on both sides of the load. This can result in the pattern of load current flow changing as discussed with reference to figure 16. In particular there

may be a reversal of load current ramping at the point of switching which results in a discontinuity in load current. The mode transitions may therefore be implemented to avoid an unwanted discontinuity in load current. This may, in some examples, be achieved by applying a phase shift to a PWM carrier waveform used to generate the

5 PWM control signals for the output stages of the switching drivers. The phase shift may be based on the amount of change in duty cycle.

Generally the duty cycles for the drivers on both sides of the load may be generated by a modulator by comparing a modulator input with a carrier waveform, which will generally

10 be a sawtooth or triangular waveform. The input to the modulator is based on, or derived from the input signal, possibly with some adjustment to reflect the operating mode of the switching drivers – and generally the modulator input for driving one side of the load is an inverted version of the modulator input for driving the other side of the load. The modulator compares the relevant input to the carrier waveform and generates the PWM

15 control signal.

**Figure 17** illustrates two sets of example waveforms and how the timing may be controlled on a mode transition. Figure 17 illustrates a carrier waveform, in this example a sawtooth waveform that ramps up and down over the course of a switching cycle.

20 Figure 17 also illustrates the voltages  $Vx1$  at the output of the first drivers and  $Vx2$  at the output of the second driver and also the difference  $Vx1-Vx2$  and the resulting load current from the first switching driver.

Figure 17 illustrates four switching cycles and illustrates an example where, for the first

25 two cycles, both of the first and second switching drivers are operating in the first driver mode. In this example, both drivers output the relevant high switching voltage at the start of a switching cycle and then switch to the low switching voltage when the carrier waveform reaches the value of the relevant input. In the illustrated example the first driver has a relatively high duty cycle and the second driver has a relatively low duty

30 cycle. This results in periods of high and low differential voltage across the load and the current  $IR$  from the first driver ramping up and down accordingly, with the relevant periods depending on the respective duty cycles. It will be noted that in this example the load current ramps down at the end of one switching period and start of another, when both drivers are outputting the same high switching voltage.

The top set of waveforms illustrates that the first switching driver transitions to the second driver mode of operation at the end of the second switching cycle. Now, at the start of the switching cycle, the first driver is outputting the high switching voltage for the second

5 driver mode, which is higher than high switching voltage that is output by the second driver. This results in a relatively high differential voltage across the load and results in change in the load current slope which results in a discontinuity. As a result of the change in mode, the first driver now operates with a relatively low duty cycle and the duty cycle of the second driver is increased to maintain the correct differential voltage.

10

The lower set of waveforms illustrates similar operation for the first two switching cycles, but in this case at the point of mode transition there is a phase shift to the PWM carrier.

In particular the carrier is phase shifted to an extent such that the output of first switching driver is at the new low switching voltage. This keeps the voltage  $Vx_1$  of the first

15 switching driver at the same level across the mode transition and avoids a change in slope of load current. The voltage  $Vx_2$  of the second switching driver will then later

switch to the low switching voltage when the carrier reaches the appropriate level. For a sawtooth waveform, the phase shift applied (in terms of percent of the cycle period)

may correspond to the shift in duty cycle divided by two, i.e. if the change in duty cycle

20 were say 40% the phase shift may correspond to a time shift of 20% of the switching period. This maintains the same load current profile during the mode transition and avoid discontinuity.

In embodiments of the disclosure, the controller may thus be configured to control the

25 first and second switching drivers such that there is no substantial change in slope of load current from a driver output node at the point of a mode transition. The controller may be configured, on a change in driver mode, to vary an amount of a mode correction

applied to the modulator input by an amount related to the magnitude of the voltage range of the new operating mode. The controller may be configured to apply a phase

30 shift to a PWM carrier waveform on a mode transition. The phase shift applied may be based on the amount of change in duty cycle (applied to the switching driver which is not changing driver mode). When the carrier waveform is a sawtooth waveform, that ramps

from a minimum value to a maximum value and back to the minimum value over the course of a cycle period, the controller may be configured such that the phase shift

applied to the carrier waveform is proportion of the cycle period that corresponds to half the change in duty cycle for the second switching driver.

In some implementations BD-modulation techniques can be used to manage the

5 discontinuity by switching between points of equivalent ripple. That is, the switching of the first and second switching drivers may be asynchronous and the output of both of the switching drivers may be connected to the relevant high-side voltage or low-side voltage simultaneously for at least part of the switching cycle.

10 The amount of ripple in the output from a switching driver will vary over time depending on the duty cycle of switched mode driver and the peak-to-peak ripple will thus vary with duty cycle of the switching driver.

Figure 18 illustrates one example of how the peak-to-peak ripple may vary over the

15 range of duty cycles from 0 (i.e. 0%) to 1 (i.e 100%). To reduce the extent of any discontinuity as a result of a mode transition, the transition may be implemented so that the duty cycles of the switching drivers vary but maintain a substantially equal amount of ripple.

20 This could be implemented in different ways. In a first approach, the duty cycle of a switching driver could be changed from a first duty cycle D1 to a second duty cycle D2, where the duty cycles D1 and D2 exhibit substantially the same peak-to-peak ripple as one another. This is illustrated by transition 1801 in figure 18 which indicates that the

25 duty cycle of the switching driver could be varied from a first duty cycle D1 to a second duty cycle D2, the first and second duty cycles being selected to provide equal amounts of ripple.

In a second approach, the duty cycles of both switching drivers could be changed so that the amount of ripple seen differentially across the load stays constant. For instance, as

30 illustrated by transition 1802 in figure 15, the duty cycle of the first switching driver could be varied from a first duty cycle D3 to a second duty cycle D4, say from 25% to 75%, whilst the duty cycle of the second switching driver is changed from D4 to D3, e.g. from 75% to 25%. In general the duty cycles of the first and second switching drivers may thus be varied so that an amount of ripple due to the duty cycle of the first switching

driver before the transition is the same as an amount of ripple due to the duty cycle of the second switching driver after the transition and vice versa.

In general, therefore, embodiments of the present disclosure relate to switching drivers  
5 which are suitable for driving an output transducer, that are operable to provide a drive signal with an average voltage within a defined output voltage range, e.g. between a low voltage VL and a high voltage VH. The switching driver is operable in a plurality of different driver modes, wherein in each of the modes a driver output node is switched between two switching voltages with a controlled duty cycle, wherein the switching  
10 voltages are different for each mode and the switching voltages in each mode provide only part, i.e. a subset, of the defined output voltage range.

The different switching voltages in the different driver modes may define non-overlapping voltage ranges, however this need not be the case, and, in some embodiments, there  
15 could be some overlap between the voltage ranges. For instance, the switching voltages in a first driver mode could be V1 and V2 and in a second driver mode one of the switching voltages may be a voltage which is between V1 and V2. For example the switching voltages may be 0V and 20V in a first driver mode and say 16V and 26V in a second driver mode.

20 In at least some embodiments the switching driver may comprise at least variable boost stage having first and second inputs for receiving high-side and low-side input voltages and comprising a network of switching paths and connections for a capacitor. The variable boost stage may thus be a switched capacitor stage.

25 The switched capacitor converter stage may implement a boost function as needed. When used for driving reactive loads, such as a piezo transducer, a relatively large capacitor can provide the charge needed with one charge pumping cycle.

30 The variable boost stage controls the switching voltages supplied to a switching output stage. The output stage, for instance, be controlled as a Pulse-Width Modulation (PWM) output stage. In some implementations the PWM stage may drive the load in series with an inductor, which allows lossless movement of charge between load and capacitor of the switched capacitor variable boost stage for charge recovery.

A driver circuitry according to at least some embodiments may thus be seen as a hybrid, e.g. capacitive and inductive, driver circuit.

5 The driver circuitry is configured to have floating supply domains, i.e. variable switching voltages in different operating modes, which allows for the switches of the driver circuit to have a relatively low  $V_{dsmax}$  (drain-source voltage tolerance). The driver circuit may be configured such that the MOSFET well-to-substrate breakdown voltages are sufficiently high for the peak output voltages generated in use.

10

A first boost converter may provide boosting from a supply voltage, such as a battery voltage to an intermediate supply  $VBST$  for input to the variable boost stage.

15 At least some of the embodiments described above relate to a hybrid (e.g. capacitive and inductive) driver for a reactive (e.g. piezoelectric) load, where driver comprises: a charge pump, a PWM driver, and a control system arranged to maintain linearity while transitioning the charge pump states.

20 The driver may be operable to produce  $N$  times the peak-to-peak output voltage, which can be  $N$  times the  $V_{ds}$  breakdown voltage of the devices by driving the deep  $N$ -wells in a signal dependent manner (where  $N = 6$ , for example).

25 At least some embodiments relate to a hybrid driver for a reactive load such as a piezoelectric transducer, where the driver is arranged to receive an input signal and to generate an output signal for driving the reactive load, the hybrid driver comprising: a driver stage, which may, for example, be a Pulse-Width-Modulation (PWM) driver, the driver stage arranged to receive the input signal and to generate the output signal for driving a reactive load. The driver may also comprise a variable boost stage, such as a charge pump stage, arranged to generate a voltage supply range for the driver stage based on a supply voltage, and the charge pump stage may be controlled such that the voltage supply range is based on the range of the received input signal.

The driver may further comprise a first define boost stage or power converter stage, e.g. a DC/DC Boost Converter, the power converter stage arranged to receive a supply

voltage and to generate a boosted supply voltage, wherein the charge pump stage generates the voltage supply range based on the boosted supply voltage. The supply voltage may be from a battery or other power source.

- 5 The charge pump stage may comprise at least one capacitor, wherein the capacitor size is selected based on the reactive load to be driven, such that a single charging cycle of the capacitor provides sufficient charge for the driving of the reactive load.

Preferably, the driver stage drives an inductor arranged in series with the reactive load,  
10 wherein the inductor allows lossless movement of charge between the load and a supply capacitor for charge recovery.

The hybrid driver may be implemented in a single-ended configuration. The hybrid driver may alternatively be implemented in a bridge-tied-load (BTL) configuration, to drive  
15 opposite terminals of the reactive load. For a BTL configuration, it will be understood that the hybrid driver comprises complimentary charge pump and driver stages for either side of the load.

In at least implementations, the hybrid driver may comprise switching devices, preferably  
20 MOSFETs. In one example, N-type MOSFETs are used as the switching devices. In an alternative example, a mixture of N-type and P-type MOSFETs are used.

Preferably, the switching devices are at least partly controlled based on the signal range of the output signal. In some implementations, wells of the switching  
25 devices, e.g. deep N-wells, are driven based on the signal range of the output signal. By driving the deep N-wells of the MOSFETs, it is possible to avoid P-well to deep N-well breakdown, or forward biasing of the deep N-well to the substrate or P-well of the devices. Accordingly, the peak-to-peak output voltage of the hybrid driver can be a multiple of the  $V_{ds}$  breakdown voltage of the devices used.

30

The charge pump stage may be arranged to select a voltage supply range to be generated from a plurality of supply ranges. In some example, the charge pump stage is arranged to select between 0-20V, 20-40V, or -20-0V voltage ranges.

The hybrid driver may be controlled to apply a common mode jump to linearize the range transition. When driving the load differentially, the hybrid driver controls both the differential and the common mode voltage in order to keep both of the differential outputs in valid operating ranges and thus avoid distortion and artefacts during range transitions  
5 of the charge pump.

In some implementations, for an asymmetric differential configuration consisting of one hybrid driver and a DC source, the driver is controlled to vary the modulation index of the driver while adjusting a DC source applied to the opposite side of the reactive load to  
10 eliminate discontinuities between charge transfer phases of the charge pump stage.

For a BTL configuration, the charge pump stages of the driver may be controlled to eliminate discontinuities between charge transfer phases of the charge pump stages, for example by applying a BD-modulation to the switching of the charge pump stages.

15

There is further provided a control method for a driver, preferably for driving a reactive load such as a piezoelectric transducer, the driver comprising a plurality of MOSFET switching devices, the method comprising the steps of: receiving an input signal, and  
20 generating an output signal based on the received input signal, the output signal at least partly generated by switching of the MOSFET switching devices, wherein the method comprises the further step of: driving the wells of the MOSFET switching devices based on the signal range of the output signal, to prevent breakdown or forward biasing of the MOSFET switching devices.

25

The driver may be a hybrid driver comprising inductive and reactive elements.

The driver may comprise a set of high-voltage switches, and the step of driving the wells may comprise operating the high-voltage switches synchronously to the charge-pump  
30 during large signals.

There is also provided a system for driving a reactive load such as a piezoelectric transducer, the system comprising: a driver stage to receive an input signal and to generate an output signal for driving a reactive load, a charge pump stage arranged to

generate a voltage supply range for the driver stage based on a supply voltage, and an inductor element to be arranged in series with the reactive load such that the driver stage drives the inductor element, wherein the inductor element allows lossless movement of charge between the load and a supply capacitor for charge recovery.

5

It will be understood that the driver stage and charge pump stage may be provided by a hybrid driver as described above

10 Embodiments also relate to driver circuitry comprising two switching drivers configured to provide output drive signals for driving a bridge-tied-load.

As mentioned, the switching driver may be suitable for driving an output transducer. The output transducer may be, in some implementations, be an audio output transducer such as a loudspeaker or the like. The output transducer may be a haptic output transducer.

15 15 In some implementation the output transducer may be driven in series with an inductor, i.e. there may be an inductor in an output path between an output node of the switching driver and the load. In some implementations the transducer may be a piezoelectric or ceramic transducer.

20 20 Embodiments may be implemented as an integrated circuit. Embodiments may be implemented in a host device, especially a portable and/or battery powered host device such as a mobile computing device for example a laptop, notebook or tablet computer, or a mobile communication device such as a mobile telephone, for example a smartphone. The device could be a wearable device such as a smartwatch. The host 25 device could be a games console, a remote control device, a home automation controller or a domestic appliance, a toy, a machine such as a robot, an audio player, a video player. It will be understood that embodiments may be implemented as part of a system provided in a home appliance or in a vehicle or interactive display. There is further provided a host device incorporating the above-described embodiments.

30

The skilled person will recognise that some aspects of the above-described apparatus and methods, for instance aspects of controlling the switching control signals to implement the different modes, may be embodied as processor control code, for example on a non-volatile carrier medium such as a disk, CD- or DVD-ROM, programmed

memory such as read only memory (Firmware), or on a data carrier such as an optical or electrical signal carrier. For some applications, embodiments may be implemented on a DSP (Digital Signal Processor), ASIC (Application Specific Integrated Circuit) or FPGA (Field Programmable Gate Array). Thus, the code may comprise conventional

5 program code or microcode or, for example code for setting up or controlling an ASIC or FPGA. The code may also comprise code for dynamically configuring re-configurable apparatus such as re-programmable logic gate arrays. Similarly, the code may comprise code for a hardware description language such as Verilog <sup>TM</sup> or VHDL (Very high-speed integrated circuit Hardware Description Language). As the skilled person will appreciate,

10 the code may be distributed between a plurality of coupled components in communication with one another. Where appropriate, the embodiments may also be implemented using code running on a field-(re)programmable analogue array or similar device in order to configure analogue hardware.

15 It should be noted that the above-mentioned embodiments illustrate rather than limit the invention, and that those skilled in the art will be able to design many alternative embodiments without departing from the scope of the appended claims. The word “comprising” does not exclude the presence of elements or steps other than those listed in a claim, “a” or “an” does not exclude a plurality, and a single feature or other unit may

20 fulfil the functions of several units recited in the claims. Any reference numerals or labels in the claims shall not be construed so as to limit their scope.

Numbered Statements

Various aspects of the disclosure will be now be described by way of the following numbered statements;

5

S1. A switching driver for driving a transducer comprising:

first and second supply nodes for connection to first and second voltage supplies defining an input voltage;

10 an output bridge stage comprising a first output switch connected between a first switching voltage node and an output node and a second output switch connected between a second switching voltage node and the output node;

15 a capacitor;

20 a network of switches connecting said first and second supply nodes with said first and second switching voltage nodes and said capacitor, the network of switches being operable in different switch states to provide different voltages at the first and second switching voltage nodes, said switch states comprising:

25 a first switch state in which the capacitor is connected between the first and second supply nodes to be charged to the input voltage and the first and second switching voltage nodes are coupled to the first and second supply nodes respectively; and a second switch state in which the second switching voltage node is connected to a voltage different to that at the second supply

30 node and the capacitor is connected between the second switching voltage node and the first switching voltage node to provide a boosted voltage at the first switching node; and

a controller configured to control the switch state of the network of switches and a duty cycle of the first and second output switches of the output bridge stage based on an input signal to generate an output signal at the output node for driving the transducer.

S2. The switching driver of statement S1 wherein, in the second switch state, the second switching voltage node is connected to the first supply node.

S3. The switching driver of statement S2 wherein the network of switches is further operable in a third switch state in which the first switching voltage node is connected to the second supply node and said capacitor is connected between the second supply node and the second switching voltage node to provide a boosted voltage at the second switching node.

S4. The switching driver of statement S3 wherein the first voltage supply is more positive than the second voltage supply and the controller is configured to operate:

- in the first switch state in a first mode of operation to provide a drive signal at the output node in a range between the first and second voltage supplies;
- in the second switch state in second mode of operation to provide a drive signal at the output node in a range between the first voltage supply and the first voltage supply boosted positively by the input voltage; and
- in the third switch state in a third mode of operation to provide a drive signal at the output node in a range between the second voltage supply and the second voltage supply boosted negatively by the input voltage.

S5. The switching driver of any of statements S1 to S4 wherein the network of switches is configured such that, in use, a voltage difference across any of the switches of the network of switches and the first and second output switches is not substantially greater in magnitude than the input voltage.

S6. The switching driver of any of statements S1 to S5 wherein the network of switches is configured such a first electrode of the capacitor can be selectively connected to either of the first or second supply nodes.

S7. The switching driver of statement S7 wherein the network of switches is configured such that a second electrode of the capacitor can be selectively connected to either of the first or second supply nodes.

S8. The switching driver of any of statements S1 to S7 wherein the capacitor is connected between the first and second switching voltage nodes in parallel with the output bridge stage.

5 S9. The switching driver of statement S8 wherein the network of switches comprises:  
a first switch connecting the first supply node to a first supply select node;  
a second switch connecting the second supply node to the first supply select  
node;  
a third switch connecting the first supply select node to the first switching voltage  
10 node;  
a fourth switch connecting the first supply node to a second supply select node;  
a fifth switch connecting the second supply node to the second supply select  
node; and  
a sixth switch connecting the second supply select node to the second switching  
15 voltage node.

S10. The switching driver of statement S9 wherein the controller is configured such that, when operating in the second switch state:  
the fourth switch and sixth switch are closed, with the fifth switch open, to  
20 connect the first supply node to the second switching voltage node;  
and the second and third switches are open, with the first switch closed, so as to  
disconnect the first switching voltage node from the first and second supply  
nodes and to limit the voltage difference across any of the first to third  
switches to be not substantially greater than the input voltage.

25 S11. The switching driver of any of statements S1 to S10 wherein said capacitor has a capacitance which is large enough to store sufficient charge to supply the transducer through a cycle of the input signal.

30 S12. The switching driver of any of statements S1 to S11 wherein said capacitor is a first capacitor and the switching driver further comprises a second capacitor, wherein:

in at least one of the first and second switch states, the second capacitor is connected between the first and second voltage supplies to be charged to the input voltage;

in the second switch state, the second switching voltage node is connected to the 5 first supply node; and

the switch network is further operable in a third switch state in which the second capacitor is connected between the first supply node and the second switching voltage node to provide a boosted voltage at the second switching node and the first capacitor is connected between the second switching voltage node and the first switching voltage node to provide a 10 further boosted voltage at the first switching voltage node.

S13. The switching driver of statement S12 wherein the first capacitor is connected between the first and second switching voltage nodes in parallel with the output 15 bridge stage.

S14. The switching driver of any of statements S1 to S13 wherein at least one of the switches of the network of switches and the first and second output switches comprises an NMOS transistor where at least part of the NMOS transistor is 20 formed within an N-well in a substrate and wherein the switching driver is configured such that the N-well of the NMOS transistor is, in use, driven with a voltage based on the voltages at the first and second switching voltage nodes.

S15. A switching driver circuit comprising the switching driver of any of statements S1 to S14 as a first switching driver and further comprising a second switching 25 driver, the first and second switching drivers being configured to drive the transducer in a bridge-tied load configuration.

S16. The switching driver circuit of statement S14 wherein the second switching driver 30 comprises an output bridge stage, a capacitor and a network of switches operable in the same way as the first switching driver and wherein the controller is configured to control the switch state of the network of switches and duty cycle of the output bridge stage of both the first and second switching drivers based on an input signal to generate a differential output signal.

S17. A switching driver circuit comprising the switching driver of any of statements S1 to S14 and a DC-DC converter configured to receive at least one input voltage supply and to generate at least one of said first and second voltage supplies.

5

S18. A switching driver circuit comprising the switching driver of any of statements S1 to S14 and an inductor connected to the output node for connection in series with the transducer.

10 S19. A switching driver circuit comprising the switching driver of any of statements S1 to S14 and said transducer.

S20. An electronic device comprising the switching driver of any of statements S1 to S14.

15

S21. A switching driver for driving a transducer based on an input signal comprising:  
first and second supply nodes for connection to first and second voltage supplies defining an input voltage;

20

an output bridge stage comprising a first output switch connected between a first switching voltage node and an output node and a second output switch connected between a second switching voltage node and the output node;

a capacitor connected between said first and second switching voltage nodes in parallel with the output bridge stage;

25

a network of switches connecting said first and second supply nodes with said first and second switching voltage nodes, the network of switches being operable in different switch states comprising:  
a first switch state in which the first and second switching voltage nodes are coupled to the first and second supply nodes

30

respectively and the capacitor is charged to the input voltage;  
and

a second switch state in which the second switching voltage node is connected to a voltage different to that at the second supply node and the capacitor is connected between the second

switching voltage node and the first switching voltage node to provide a boosted voltage at the first switching node.

S22. A switching driver for driving a transducer comprising:

5           first and second supply nodes for connection to first and second voltage supplies defining an input voltage;  
an output bridge stage for selectively connecting an output node to first or second switching voltage nodes with a controlled duty cycle;  
a capacitor connected between said first and second switching voltage  
10           nodes in parallel with the output bridge stage;  
a network of switches connecting said first and second supply nodes with said first and second switching voltage nodes, wherein the network of switches is operable such that a first electrode of said capacitor can be selectively connected to either of the first and second supply  
15           nodes.

S23. A driver circuit for driving a transducer based on an input signal comprising:

first and second switching drivers with respective driver output nodes for driving said transducer in a bridge-tied-load configuration, each of the  
20           first and second switching drivers comprising a respective output stage for controllably switching the respective driver output node between high and low switching voltages with a controlled duty cycle;  
wherein each of the first and second switching drivers is operable in a plurality of different driver modes, wherein the switching voltages are different in said different driver modes; and  
25           a controller for controlling the driver mode of operation and the duty cycle of each of the first and second switching drivers based on the input signal;  
wherein the controller is configured to control the duty cycles of the first and  
30           second switching drivers within defined minimum and maximum limits of duty cycles;  
wherein the controller is configured to transition between different driver modes of operation when the duty cycle of at least one of the first and second switching drivers reaches the maximum or minimum duty

cycle limit and the controller is configured to implement the transition by changing the driver mode of one of the first and second switching drivers at said maximum or minimum limit of duty cycle and vary the duty cycle of that one of the first and second switching drivers to the other limit of duty cycle whilst maintaining the driver mode of the other of the first and second switching drivers and applying a variation in duty cycle to maintain a magnitude of a differential component of the first and second driver signal.

10 S24. A driver apparatus for driving a transducer comprising:  
a first switching driver having a first driver output node for driving the transducer, wherein the first switching driver comprises a first output bridge stage for selectively switching the first driver output node between high and low switching voltages,  
15 a first modulator for controlling a duty cycle of switching of the first output bridge stage based on an input signal; and  
a first voltage controller for providing said switching voltages;  
wherein the first switching driver is operable in a plurality of driver modes of operation in which the first voltage controller is operable to provide different switching voltages in each driver mode; and the apparatus comprises:  
20 a controller for controlling the driver mode of operation and the duty cycle of the first switching driver based on the input signal, wherein the controller is configured to transition between said driver modes of operation from a present mode to a new mode by:  
25 controlling the first voltage controller to provide the switching voltages for the new mode; and  
controlling the first modulator to vary the duty cycle of the first output bridge stage, wherein the change in duty cycle is controlled such that there is no substantial discontinuity in switching ripple.

30

CLAIMS

1. A driver circuit for driving a transducer based on an input signal comprising:
  - first and second switching drivers with respective driver output nodes for
  - 5 driving said transducer in a bridge-tied-load configuration, each of the first and second switching drivers comprising a respective output stage for controllably switching the respective driver output node between high and low switching voltages with a controlled duty cycle;
  - wherein each of the first and second switching drivers is operable in a plurality of different driver modes, wherein the switching voltages are different in said different driver modes; and
  - 10 a controller for controlling the driver mode of operation and the duty cycle of each of the first and second switching drivers based on the input signal;
- 15 wherein the controller is configured to control the duty cycles of the first and second switching drivers within defined minimum and maximum limits of duty cycles;
- wherein the controller is configured to transition between different driver modes of operation when the duty cycle of at least one of the first and second switching drivers reaches the maximum or minimum duty cycle limit and the controller is configured to implement the transition by changing the driver mode of one of the first and second switching drivers at said maximum or minimum limit of duty cycle and vary the duty cycle of that one of the first and second switching drivers to the other limit of duty cycle whilst maintaining the driver mode of the other of the first and second switching drivers and applying a variation in duty cycle to maintain a magnitude of a differential component of the first and second driver signal.
- 20
- 25
- 30 2. The driver circuit of claim 1 wherein the maximum limit of duty cycle is 95% or less and the minimum limit of duty cycle is 5% or greater.
3. The driver circuit of claim 1 or claim 2 wherein the difference between the switching voltages is the same in each of the different driver modes.

4. The driver circuit of any preceding claim wherein each of the first and second switching drivers are operable in:

a first mode in which the switching voltages are a first voltage V1 and a second voltage V2, where the first voltage is more positive than the second

5 voltage; and at least one of:

a second mode in which the switching voltages are the first voltage V1 and a voltage which is more positive than the first voltage V1; and

a third mode in which the switching voltages are the second voltage V2 and a voltage which is more negative than the second voltage V2.

10

5. The driver circuit of claim 4 wherein each of the first and second switching drivers have first and second supply nodes for receiving first and second supply voltages, and the first and second switching drivers are configured such that the first voltage V1 and the second voltage V2 are equal to the supply voltages

15 received at the respective first and second supply nodes.

6. The driver circuit of claim 4 or claim 5 wherein the controller is configured to control the driver modes of the first and second switching drivers to provide a plurality of BTL modes comprising:

20

a low-signal mode in which both the first and second switching drivers operate in the first driver mode;

an intermediate-signal mode in which one of the first and second switching drivers operate in the first driver mode and the other one of first and second switching drivers operates in either the second driver mode or the third driver

25

mode; and/or

a high-signal level mode in which one of the first and second switching drivers operates in the second driver mode and the other one of first and second switching drivers operates in the third driver mode.

30

7. The driver circuit of claim 6 wherein the controller is configured such that, in each of the BTL modes of operation, the controller controls the duty cycles of the first and second switching drivers so that a common-mode component of first and second drive signals at the respective driver output nodes of the first and second switching drivers does not substantially vary with signal level.

8. The driver circuit of claim 7 wherein the controller is configured such that the common-mode component of first and second drive signals when operating in the low-signal mode is substantially the same as the common-mode component of the first and second drive signals when operating in the high-signal mode, but different  
5 to the common-mode component of first and second drive signals when operating in the intermediate-signal mode.
9. The driver circuit of any preceding claim wherein the controller is configured to control the duty cycles of the first and second switching drivers before and after a  
10 transition in mode such that a common-mode component of the voltage across the transducer differs before and after the transition.
10. The driver circuit of any preceding claim wherein each of the first and second switching drivers comprises a variable boost stage selectively operable to provide  
15 voltage boosting to provide a voltage for use as a switching voltage in at least one of the different driver modes.
11. The driver circuit of claim 10 wherein each of the first and second switching drivers comprises first and second supply nodes for receiving first and second supply  
20 voltages and the variable boost stage of each of the first and second switching drivers comprises at least one capacitor and a network of switches for connecting the first and second supply nodes with the capacitor and the respective output stage.
- 25 12. The driver circuit of claim 11 wherein the network of switches is operable in one switch state in which the at least one capacitor is connected between the first and second supply nodes to be charged to the input voltage and in at least one switch state where the at least one capacitor is connected in series with one of the first and second supply nodes to provide a boosted voltage as one of the switching  
30 voltages.
13. The driver circuit of any preceding claim further comprising at least a first inductor connected to the driver output node of the first switching driver for connection in series with the transducer.

14. The driver circuit of any preceding claim wherein the transducer is at least one of: an audio output transducer, a haptic output transducer, a piezoelectric transducer, and a ceramic transducer.
- 5 15. An electronic device comprising the driver circuit of any preceding claim.



**Application No:** GB2418671.0

**Examiner:** Gillian Buggey

**Claims searched:** 1-15

**Date of search:** 11 April 2025

## Patents Act 1977: Search Report under Section 17

### Documents considered to be relevant:

Category	Relevant to claims	Identity of document and passage or figure of particular relevance
A	-	US 2013/0223651 A1 (HØYERBY) See the whole document, especially figures 4-8 & 11 and paragraphs [0104-0105], [0115] & [0138-0140].
A	-	US 2013/0099859 A1 (CERUTTI) See figures 1, 4-7 and the associated description.

### Categories:

X	Document indicating lack of novelty or inventive step	A	Document indicating technological background and/or state of the art.
Y	Document indicating lack of inventive step if combined with one or more other documents of same category.	P	Document published on or after the declared priority date but before the filing date of this invention.
&	Member of the same patent family	E	Patent document published on or after, but with priority date earlier than, the filing date of this application.

### Field of Search:

Search of GB, EP, WO & US patent documents classified in the following areas of the UKC<sup>X</sup> :

Worldwide search of patent documents classified in the following areas of the IPC

H02M; H03F

The following online and other databases have been used in the preparation of this search report

SEARCH-PATENT

### International Classification:

Subclass	Subgroup	Valid From
H03F	0003/217	01/01/2006
H02M	0001/12	01/01/2006
H02M	0007/42	01/01/2006
H02M	0007/483	01/01/2007
H02M	0007/5387	01/01/2007
H02M	0007/5395	01/01/2006
H03F	0003/183	01/01/2006