Integrated differential high-voltage transmitting circuit for CMUTs

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Abstract—In this paper an integrated differential high-voltage transmitting circuit for capacitive micromachined ultrasonic transducers (CMUTs) used in portable ultrasound scanners is designed and implemented in a 0.35 µm high-voltage process. Measurements are performed on the integrated circuit in order to assess its performance. The circuit generates pulses at differential voltage levels of 60 V, 80 V and 100 V, a frequency up to 5 MHz and a measured driving strength of 1.75 V/µs with the CMUT connected. The total on-chip area occupied by the transmitting circuit is 0.18 mm² and the power consumption at the scanner operation conditions is 0.754 mW without the transducer load and 0.936 mW with it.

I. INTRODUCTION

Ultrasound scanners are widely used in medical applications since it is a very effective and fast diagnostic technique. The traditional static ultrasound scanners are large devices which are plugged into the grid. Therefore they have no power consumption limitation, hence the design tendency is to keep increasing their complexity to obtain better picture quality. In the last decade, high integration has enabled portable ultrasonic scanners to have comparable performance to the traditional static ultrasound scanners. However, portable scanners have power consumption, heat dissipation and area limitations. Consequently, the main target of the design of a portable ultrasound scanner is to utilize the power consumption budget and area available in the most effective way in order to achieve the best picture quality possible.

Ultrasonic scanners consist of hundreds of channels and each of them has a transducer, a transmitting circuit (Tx) and a receiving circuit (Rx). The Tx provides the high-voltage pulses that the transducer needs to generate ultrasonic waves and the Rx detects the low voltage signal induced in the transducer and amplifies it and digitizes it. The ultrasound transducers used in this paper are capacitive micromachined ultrasonic transducers (CMUTs), [1], which are composed of a thin movable plate suspended on a small vacuum gap on top of a substrate. The transducer has two terminals, one connected to the substrate and the other connected to the movable plate. By applying a voltage difference between the two terminals of the CMUT, the thin plate deflects due to an electrostatic force. The ultrasound is generated when applying high-voltage pulses in one of the terminals of the CMUT which makes the thin plate vibrate.

This paper deals with the design and implementation of an integrated differential high-voltage transmitting circuit for CMUTs, and it is an improved version of the work presented in [2].

II. TRANSMITTING CIRCUIT SPECIFICATIONS

The transmitting circuit needs to drive a particular CMUT, therefore its specifications come from the inherent transducer characteristics. The CMUT has been designed and modeled at DTU Nanotech, and even though the driving requirements are described here, the electrical equivalent model of the CMUT is confidential, therefore it is not presented in this paper. The CMUT, which is mainly a capacitive load, has an equivalent capacitance of 30 pF and has a resonant frequency of \( f_r = 5 \text{ MHz} \). In receiving mode, the transducer needs a bias voltage of 80 V and during transmission, the CMUT requires high-voltage pulses from 60 V to 100 V toggling at its resonant frequency and a driving strength corresponding to a slew rate (SR) of 2 V/µs. Ultrasound scanners transmit for a short period of time, 400 ns, and receive for a much longer period of time, 106.4 µs, hence the operation transmitting duty cycle is 1/266 in this particular application.

III. DESIGN AND IMPLEMENTATION OF THE TX

The transmitting circuit designed in this paper consists of new and improved subcircuits structured in the same way as in [2], which is shown in Fig. 1. The Tx consists of a three-level high-voltage output stage that drives the ultrasonic transducer, which is controlled with high-voltage signals provided by the level shifters. The low-voltage signals needed for the level shifters operation are generated by the control logic block. A smaller differential output stage topology with superior performance is used together with an improved version of the level shifters which consume much less current and occupy less area. A more advanced control logic block is also used which internally synchronizes the input signals and compensates for the delay of the level shifters in order to avoid possible shoot through in the output stage by accidentally turning on several MOS devices at the same time. All the reconfigurability features presented in [2] are also removed in order to improve the power consumption and diminish the area of the transmitting circuit, hence the Tx is designed to drive the specific CMUT

![Fig. 1. Transmitting circuit block structure.](image-url)
that was described in Section II. In the next subsections the
design of each block of the improved Tx circuit is presented.

A. Differential output stage

CMUTs are non-polarized devices, therefore they can be
single-ended driven by pulsing one of the plates and biasing
the other or differential driven by pulsing both terminals, which
is the approach used in this design. The most commonly used
single-ended approach [3] used also in the previous output
stage [2] had some drawbacks. Firstly, two transistors were
required to connect the output node to the middle voltage,
an NMOS to pull down from high-voltage and a PMOS to
pull up from low voltage. Secondly, two extra diode-coupled
MOS devices were needed in order to avoid short circuiting
voltage supplies through the body diode of the MOS transistors
connected to the middle voltage. These diode-coupled MOS
devices also added a small voltage drop that caused a small
offset from the middle voltage level in the output node.

In order to solve the aforementioned problems and improve
the area and power consumption of this block a new differential
output stage topology was designed and its schematic can be
seen in Fig. 2. It consists of two two-level output stages, each
of them connected to one of the terminals of the transducer,
that can generate three differential levels. There are several
advantages of this topology. Firstly, the number of transistors
used is only four, instead of the six used in the single-ended
version, which translates into less area and also less parasitic
capacitance. The two diode-coupled MOS devices are not used
anymore so there is no voltage offset from the voltage supplies
to the output node connected to the CMUT. Secondly, since
CMUTs are mainly capacitive loads, the two sides of the
output stage are DC voltage isolated, therefore the voltage
swing that each side needs to handle is only a drain-source
voltage of 20 V instead of the single-ended version where
some of the MOS devices of the output stage needed to
handle the full pulse swing. Since the voltage requirements
are lower, the MOS devices can also be smaller and with
less parasitic capacitance which improves the area and power
consumption. Thirdly, since the CMUT is driven differentially,
the slew rate required in each side of the output stage is
reduced to 1 V/ns, which is half of the slew rate specified in
Section II. The slew rate required is related to the size of the
MOS devices, hence reducing the SR requirements will allow
for smaller device parameters. This topology also presents
potential advantages such as four level pulsing achieved by
using non-symmetrical voltages. Increasing the number of
voltage levels can be beneficial for the power consumption, as
shown in [3]. There is one consideration to be made regarding
the differential topology, which is the need of an extra pad
in the integrated circuit since it needs to be connected to the
two terminals of the CMUT instead of one. In principle, this
would require a full extra high-voltage ESD protected pad,
which occupies approximately 0.11 mm². However, the output
stage transistors are significantly large, hence their inherent
ESD protection was tested and proved to be enough in order
to protect the integrated circuit. Only a small pad opening of
0.025 mm² placed on the top of the output stage is required to
connect the transducer to the integrated circuit occupying no
additional area.

The MOS devices $M_1$, $M_2$, $M_3$ and $M_4$ are sized in order
to achieve the SR of 1 V/ns in each side of the differential
output stage for all the different voltage transitions. The SR
was measured with the CMUT connected since its impedance
affects the performance of the output stage. Another consid-
eration during the sizing of the output stage transistors is the
maximum peak current. It needs to be guaranteed that each
MOS device can handle the maximum peak current without
being destroyed.

B. Improved pulse-triggered level shifters

The output stage contains four MOS devices, $M_1$, $M_2$, $M_3$ and $M_4$ and they are driven with different voltage levels
$V_{Hi}$: 100 V, 80 V, 20 V and 5 V. Each MOS device requires
a level shifter which needs to be optimized and designed for
that specific voltage. A low-power pulse-triggered topology is
used for the three high-voltage level shifters and a conventional
cross coupled low-voltage topology is used for the 5 V level
shifter since its power consumption and area are negligible
(not shown here due to its simplicity).

The previous pulse-triggered level shifters that were used
in [2], even though they were functional, presented some
problems such as large area due to the high gate-source voltage
range, unregulated current pulse magnitude that changes the
state of the latch and latch start-up state issues when ramping
the high-voltage domain of the level shifter. In order to
overcome some of these problems a new improved version
of the pulse-triggered level shifter presented in [4] is used in
this transmitting circuit and its schematic is shown in Fig. 3.
The first change from the previous level shifters is a reduced
gate-source voltage swing from 12.5 V to 5 V that allows for
the usage of MOS devices with thinner gate oxide which are
smaller and have less parasitic capacitances. Consequently
$V_{LO} = V_{HI} - 5$ V. Furthermore, using these devices, now the
floating current mirror and the latch can be collected in a single
deep N-well reducing significantly the area of the design. The
second change is the addition of a current mirror formed by
$M_{1a}$, $M_{1b}$, $M_{1c}$ and $M_{1d}$ that controls the magnitude of the
current pulse that changes the state of the latch. This allows
for a smaller magnitude of the current pulse as it can be
controlled from a bias generator with reduced process, voltage
and temperature dependence, hence there is no need to over-
design it for the worst case process corner. The last change in
the level shifters is the addition of common mode clamping
transistors $M_7$ and $M_8$ to reduce the common mode current
transferred to the latch when the high-voltage domain of the
level shifter is ramping [5]. Using these two extra MOS devices the design is more robust to high-voltage ramping. It is worth to mention that since each level shifter is designed for a different voltage level, the delay from the input to the output of each of them is different. Consequently the delays needs to be compensated in the low-voltage control logic block, to avoid shoot through in the output stage.

C. Low-voltage control logic

The low-voltage control logic consist of three parts which are shown in Fig. 4: Synchronization, delay compensation and pulser. Firstly, the input signals, $s_i$, are synchronized to avoid any effect of external routing and also ensure 50% pulsing duty cycle even if the input signals $s_i$ are not exact. The synchronization is performed on-chip using standard cell flip-flops clocked at double frequency of the pulses, $f_{clk} = 2f_{t} = 10$ MHz. Secondly, the synchronized signals $s_i'$ are separately delayed in order to compensate for the different delays of the level shifters and also a common delay is added as dead time to avoid shoot through in the output stage by having two MOS devices on at the same time. The delays are implemented with standard cell minimum size inverters for area reduction and power consumption purposes. Finally, the synchronized and delay-compensated signals, $s_{i''}$, are converted into pairs of set/reset signals, $s_{set,i}$ and $s_{reset,i}$, to properly drive the pulse triggered level shifters. The pulsing circuit used is the same mentioned in [2].

![Fig. 4. Block structure of the low voltage control logic.](image)

IV. MEASUREMENT RESULTS

After the design, the transmitting circuit was taped out and fabricated in a 0.35 µm high-voltage process, and a picture of the integrated circuit die taken with a microscope can be seen in Fig. 5. Two full transmitting circuits were included in the die, one with ESD protected pads and a second one with just pad openings, in order to assess the inherent ESD protection of the output stage. The inherent ESD protection proved to be sufficient, therefore the measurements were performed with the transmitting circuit without ESD protected pads. The low-voltage control logic is located in area a) with an area of 0.01 µm², the level shifters are situated in area b) with an area of 0.059 mm² and the differential output stage is located in c) and occupies an area of 0.055 mm². The total area of the transmitting circuit accounting also for the routing is 0.18 mm².

In order to assess the performance of the transmitting circuit a PCB was built to test it. The measurement setup used is shown in Fig. 6. Two Hewlett Packard E3612A voltage supplies were used to generate 20 V and 100 V, and from those voltages the on-board linear regulators generate the rest of the voltage levels used in the integrated circuit, 5 V, 15 V, 80 V, 85 V and 95 V. During the current measurements, only the current from each voltage level fed into the chip was accounted, hence the current sunk by the linear regulators was not considered. The low-voltage input signals and the low-voltage supply were generated using an external Xilinx Spartan-6 LX45 FPGA with a maximum clock frequency of 80 MHz and 3.3 V operation. The voltage outputs of the Tx connected to the CMUT and the current consumption were measured using a Tektronix MSO4104B oscilloscope and a Tektronix TCP202 current probe.

Using the described setup, the integrated circuit was tested with pulses from 60 V to 100 V, frequency of 5 MHz, a receiving bias voltage of 80 V and ultrasound scanner transmitting duty cycle of 1/266. The measured voltage of the two terminals of the CMUT and the differential voltage between the plates of the CMUT can be seen in Fig. 7. The bias voltage is stable around 80 V when receiving and it toggles according to the input signals supplied between 60 V and 100 V at a measured frequency of 4.995 MHz when transmitting.
The minimum slew rate measured in the high-voltage terminal of the Tx is 0.92 V/ns and the slew rate measured in the low-voltage terminal is 0.83 V/ns, which are a bit below the specified 1 V/ns. This slightly reduced slew rate is attributed to the parasitic capacitance of external routing and the probe capacitance used to measure. In order to measure the power consumption, the currents from all the voltage levels supplying the integrated circuit were measured both for the unloaded Tx and also for the Tx with the equivalent electric model of the CMUT connected. The measurements are shown in Table I. The currents measured from the 5 V, 15 V, 85 V and 95 V supplies were negligible compared to the ones measured in the other voltage supplies, so they are accounted as zero and are not shown in the table. Using these current measurements, the power consumption can be calculated obtaining 0.754 mW for the unloaded Tx and 0.936 mW once loaded.

V. DISCUSSION

The design presented can not be compared directly with state of the art transmitting circuit since the references found either do not specify the driving conditions, area and power consumption or only the full channel consumption, including the receiving circuitry, is stated [6], [7]. A comparison with the previous Tx presented in [2] is performed. However, the operation conditions on the previous Tx were different: The pulse voltage swing was 50 V and the duty cycle was 50%. In order to compare the topologies, the same operating conditions should be defined. The conditions chosen are the ones closest to the operation of an ultrasound scanner such as the ones defined in this paper: pulse voltage range of 40 V, pulsing frequency of 5 MHz, and a transmitting duty cycle of 1/266. Adjusting the power consumption in the previous Tx to the operation conditions of an ultrasound scanner, a comparison can be performed and a summary is shown in Table II. The power consumption corresponds to the non-loaded transmitting circuits, and a probe with the same 15 pF capacitance was used in both cases. The improved differential Tx presented in this paper achieves a very significant area reduction of 80.8% and the power consumption is reduced 58.2%.

VI. CONCLUSIONS

In this paper a differential integrated high-voltage transmitting circuit for CMUTs is designed and implemented in a high-voltage 0.35 µm process. The circuit supplies pulses with a frequency of 5 MHz, voltage levels of 60 V, 80 V and 100 V and a measured slew rate of 1.75 V/ns. The transmitting circuit is measured under the operation conditions of an ultrasound scanner in order to accurately assess the performance of the circuitry. The non-loaded total power consumption measured on the integrated circuit is 0.754 mW and the circuit occupies an on-chip area of 0.18 mm², which represent an improvement of 58.2% and 80.8% respectively from the previous design.

REFERENCES


