Current-Controlled Slew-Rate Adjustable Trapezoidal Waveform Generators for Low- and High-Voltage Applications

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***Abstract*—An approach to design of a current-controlled slew-rate adjustable trapezoidal waveform generators is presented. The paper presents circuit abilities of control over shape of output waveform, as well as possibility of a generator adaptation for operation in high-voltage applications, without any profound structure modifications.**

***Index Terms*—trapezoidal waveform generation, current-mode operation, high-voltage IC, slew-rate control**

I. Introduction

SYSTEMS of wireless mode digital signal transmission utilize various input signal shapes. Simple sinusoidal waveforms are not always well suited for straightforward digital signal transmission. More "digitally shaped" signal should be used. Such signals can be easily received and interpreted. Square waveforms, on the other hand, due to their shape, produce large amounts of high-frequency harmonics. This can exclude such transmitter from market because of norm-excessive electromagnetic distortions related to its operation. A kind of intermediate signal is a trapezoidal waveform. Although, there is some amount of high-frequency harmonics, it can be further reduced as a spectrum of the signal is located mainly in low frequency range. Trapezoidal waveforms are also utilized in numerous other applications, e.g. liquid crystal displays [3], which makes presented solutions even more interesting.

Signal speed and spectrum properties can be measured and characterized by means of slew-rate value of the trapezoidal waveform. It is not uncommon for various solutions to treat slew-rate value as an important specification parameter. Both stability of slew-rate value and its value itself may be strictly defined. E.g. 0.5% stability of output waveform slew-rate value over 80% of the waveform voltage-range is a tight but sometimes utilized requirement.

Various systems of wireless transmission work with signals of different frequency. In case of a trapezoidal waveform generation, simple change of signal repetition frequency is not enough. Also, a slew-rate value should be adjusted to retain required signal shape and properties. Including such ability into a single waveform generator makes it more universal device and expands its applicability, which is an obvious virtue.

All the simulations presented in the paper are made using the SMART-I.S.(R) SOI process, with EKV device models. All circuits are powered with 5V supply voltage.

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II. Operation Rule

There are several approaches to problem of trapezoidal waveform generation. Many of them are voltage-mode solutions [1]. The approach presented in the paper is rather a current-mode based approach to the problem. The very operation rule is a consecutive charging and discharging of an output capacitor, with use of a current source or sources, as sketched in Fig. 1. Final effect is a constant slew-rate voltage waveform while current charges / discharges a capacitor and a constant value voltage signal when there is no current flow to/from the capacitor.

The big advantage of such approach is fact, that the slew-rate parameter value is controlled with an DC current value, due to charge summing operation of the output capacitor. Such DC value is a convenient control mean. Such current can be either easily produced inside an ASIC, or provided from outside of the ASIC.

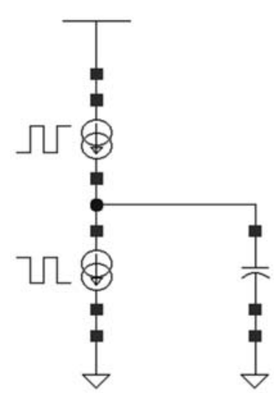

Fig. 1. Rule of trapezoidal waveform generation.

Practically, instead of current source, rather a set of two current mirrors is utilized. One of them sources current to the output capacitor and the other sinks current flow from the capacitor. Similar concept is known to be included in a few specialized solution, some of the were even patented [2]. The operation rule itself is very simple but offers quite interesting set of properties if used in modern integrated circuits [4].

As presented, two main waveform generator parts are: current mirrors (sources) and an output capacitor. Operation precision of both these two components decides precision of the whole waveform generator. A dependence of output signal quality on current mirror operation is obvious. The higher current mirror output impedance the more stable slew-rate value over whole voltage-range at the output. It is so because any output current of high-quality mirror changes little with change of voltage at its output.

Influence of the capacitor quality may not be so obvious at first glance. Capacitor as a discrete device is usually seen as a one having constant capacitance regardless voltage drop between its terminals. In case of and integrated circuit capacitor realization, situation is more complicated and capacitors, like MOS-based devices, are not well suited for precise applications.

III. Low-voltage Generators

As pointed earlier, the idea of circuit is just a set of current sources or mirrors and an output capacitor. Such functionality can be realized by a number of topologies. Some of them are usually connected to quite different applications.

A. *OTA-based example of generator structure*

Interesting example of applicable structure is an OTA - operational transconductance amplifier. Such structure is presented in Fig. 2.

The OTA can be used for trapezoidal waveform generation without any topology modifications. As a waveform generation circuitry it works in an open-loop configuration with only a capacitor as a load. The differential-pair transistors act as a pair of consecutively switching keys. The signal produced by such circuitry is presented in Fig. 3.

Derivative of this signal, being equivalent to a slew-rate value, is presented in Fig. 4. It can be seen that OTA works with no problem in this unusual application. For proper signal quality, output stage of the OTA is equipped with cascode current mirrors. The signal produced by the OTA is a trapezoidal waveform limited by supply and ground voltage levels. One specific behavior of this waveform can be observed when it reaches its extreme values i.e. it reaches either supply or ground level.

Waveform becomes rounded if an output voltage approaches limits. It is so due to fact, that as output voltage approaches one of power levels, current mirror output currently charging-discharging the output capacitor becomes gradually switched-off. Operating points of output mirror transistors leave saturation region, sweep through linear region and finally pass into off state. When voltage level of the output waveform starts to leave supply and ground levels there are no such phenomena. In this situation the opposite current mirror starts charging/discharging the output capacitor with a large voltage at its output. Such shape distortion can cause problems in application, but usually such circuit behavior can be amended through relevant circuit modifications or in course of further signal processing. Solutions to this phenomenon are presented later in this paper.

Of course, presented OTA-based structure is just one of possible generator realizations. It contains just what is needed for a process trapezoidal waveform generation: a redirected current flow and two current mirrors able to source and sink currents to and from the output capacitor.

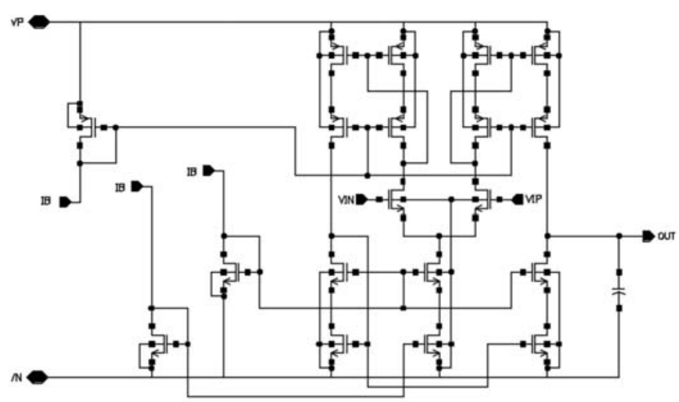

Fig. 2. OTA-based waveform-generator.

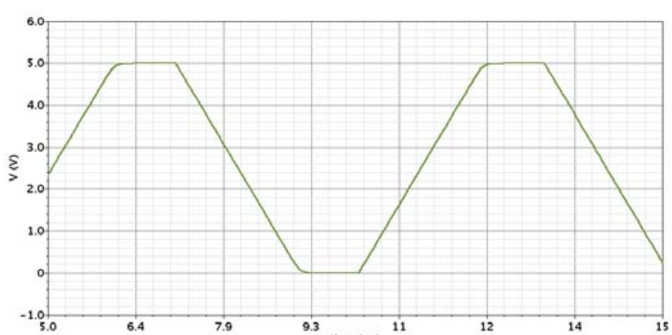

Fig. 3. Output waveform of Fig. 2 generator.

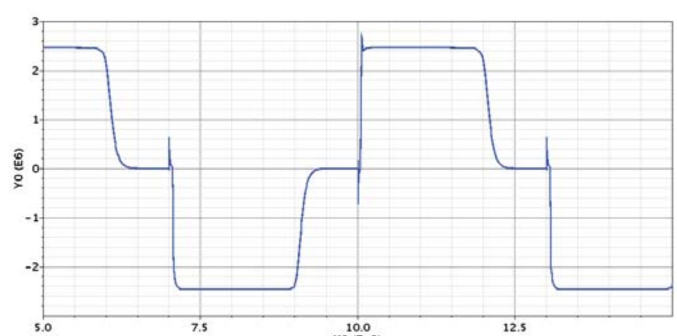

Fig. 4. Derivative of output waveform of Fig. 2 generator.

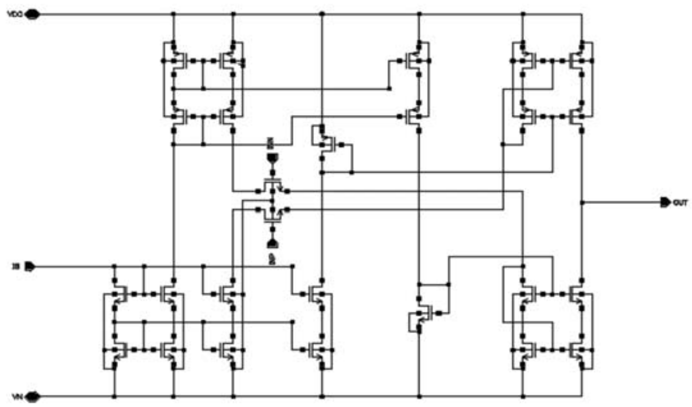

Fig. 5. Simple waveform generator based on current-mirrors.

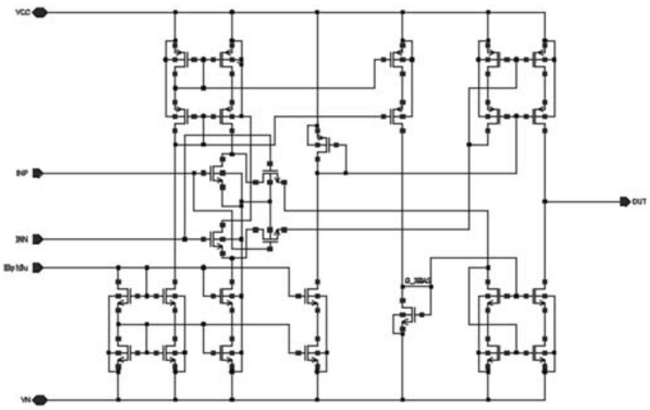

Fig. 6. Modified waveform generator based on current-mirrors.

B. Current-switching based generator structures

Fig. 5. shows different structure of waveform generator. There is no differential-pair and switches just cut off the current-flow. It is very simple structure but is inferior to the OTA based generator in one aspect. Inside the OTA-based solution there is only one current and it is redirected between two signal paths inside the OTA. In the latter solution there are two currents and their flow is blocked, according to needs. The OTA based generator does not block any currents, owing to this, power consumption of this generator changes in a less rapid way. Also, current mirrors inside this generator undergo smaller stresses during signal generation cycle. In the latter structure (Fig.5) current mirrors inside the generator are forced to extinguish their current flow when switches go off. After an appropriate switch goes on, the relevant current mirror needs some time to regain its proper operation. Fortunately, this drawback can be removed in various ways.

Fig. 6 shows structure with additional switches that redirect a current that is not needed. Though it works, four switches are required instead of two. Fig. 7. depicts potential of current mirror based generator structure. First of all, another approach to current flow control is implemented. There are no current blocking switches here. The two switches present here act as bypass devices. If such switch is off, a current flows through relevant current mirror. When the switch goes on, an input of current mirror is shortcircuited to the ground level. Owing to this the current mirror is turned off but its input current still can flow through the conducting switch and its flow is uninterrupted.

There is more flexibility in the generator structure of Fig. 7. This circuitry is equipped with two inputs for slew-rate defining DC currents. Owing to this feature various non-symmetrical waveforms can be generated. Also, the circuitry is driven with two independent digital control inputs. It enables a more sophisticated control over waveform forming. Both rising and falling of output voltage may be paused and then either resumed or reversed. There is also possibility of switching on both output mirrors that feed the output capacitor. At first it can be seen as a risk, not a benefit. But, there is an application for such a control mode.

Sometimes it can be required to produce very slow and a stable voltage ramp. In case when the output capacitor is placed inside an IC and its value cannot be modified, only control over slew-rate can be obtained through the DC current value. Unfortunately, a low value current is not well suited for a multiple copying process. When mirror transistors operate with low currents, they hardly conduct and their operating points are close to operation region borders. Result is that output current value may less precisely follow the input value. Errors of current mirroring accumulate with every such process required between control DC current generation or application point and output capacitor of the generator.

To retain proper current quality some extra action is needed. The simplest solution is just to provide both control currents to the output capacitor, same time. The result it that two precisely copied currents are subtracted at the very capacitor. Low slew-rate signal generation ability is possible without any changes inside the generator itself.

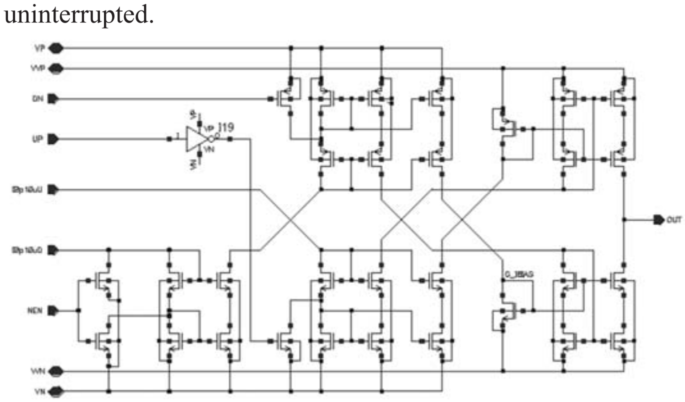

Fig. 7. Waveform generator equipped with bypass switches.

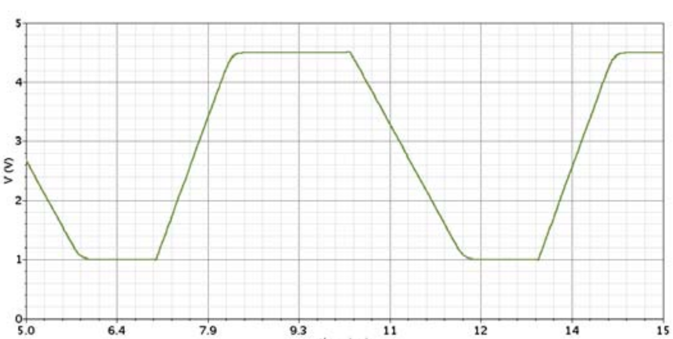

Fig. 8. Limited voltage-range waveform produced by Fig. 7 generator.

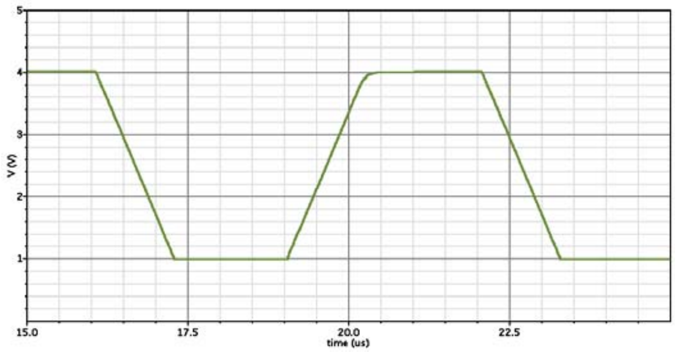

Fig. 9. Waveform produced by Fig. 7 generator with externally controlled current flow stopping.

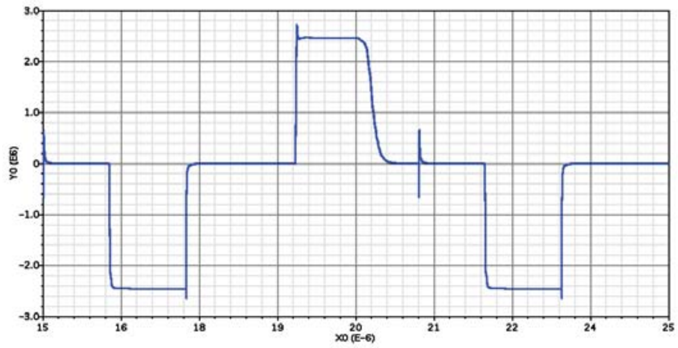

Fig. 10. Derivative of waveform produced by Fig. 8 generator with externally controlled current flow stopping.

C. Further processing of generated waveforms

Other change in the circuit presented in Fig. 7 are distinct connections for the output mirror supply and ground nodes. Such modification enables control over a voltage-range of the generator output signal. Often the output waveform voltage-range is not rail-to-rail but is limited, though usually placed centrally in voltage space. Simplicity of this voltage-range controlling circuitry add-on is related to a fact, that due to a current-mode of operation of generator output stage, it can be connected to various supply and ground voltage levels without any further circuit modifications. It is enough to provide simple virtual supply and ground modules driven with required limiting voltages. Simple voltage regulators based on OPAMPs with properly designed output stages are enough as virtual supply and ground providers. Voltage range of waveform generated at the generator output is now strictly limited to virtual power levels, at which the output current mirrors fully extinguish themselves (Fig. 8).

All waveform generators presented so far exhibit same output signal distortion already mentioned in this paper. The output waveform is slightly rounded when waveform voltage approaches its limits. This can be a problem in some applications. Fortunately, this phenomenon can be easily removed, at least for not rail-to-rail waveforms.

Improvement of the output waveform shape can be provided by the very circuitry that provides the voltage-range limiting functionality. The circuitry that provides both voltage limiting and shape improvement functionality is one external to the generator itself and based on a flow control of capacitor charging/discharging currents.

If these currents are switched-off abruptly, the charging/discharging process stops suddenly and no waveform rounding effect is introduced. The waveform produced with such mean of control is presented in Fig. 9. Its derivative is presented in Fig. 10. In can be observed that the slew-rate value for this waveform goes down to zero in a quick manner.

Sometimes, trapezoidal waveform needs further shaping in order to meet circuit specification. One of such modifications is required for electromagnetic compatibility sake. Trapezoidal waveform produces some high frequency noise. If such waveform is fed into an antenna, high frequency electromagnetic waves are generated. This may cause many problems and should be avoided. The noise is related to the sharp edges of the trapezoidal waveform. So, these edges need to be in a way removed or rather rounded. So, the process is referred to as the edge-rounding. One possible way of such edge rounding utilizes generation of rail-to-rail, or generally a wide voltage-range, trapezoidal waveform that is non-linearly processed. Due to such a process parts of waveform close to power levels are "compressed" to fit into a limited voltage range required for final waveform [5]. This process of original waveform distortion produces the rounding effect. As the waveform shape is compressed for extreme voltages, the previously mentioned slightly rounded shape of produced waveform even helps signal rounding efforts.

IV. High Voltage Generators

Current mode of the presented generator concept enables efficient construction of high-voltage version of generator. Because all or most of waveform-forming information can be placed inside two currents that charge and discharge output capacitor, there is no need of a deep circuit reconstruction, which could be needed in case of voltage-mode operating circuits.

Numerous technology processes provide high-voltage passive and active devices, able to operate with voltages as high as tens of volts. Unfortunately, a usual limitation for majority of MOS devices in such processes is maximum a gate-source voltage. Often the limit is approximately equal 5V. As MOS devices are voltage-controlled ones and usually a control is imposed in form of gate-source voltage adjustment, these high-voltage MOS transistors are still low-voltage controlled. In case of circuitry composed of current mirrors, proper design may limit high-voltage drop presence to only gate to drain connections. A gate-drain voltage is not as limited as in case of gate-source voltage, and can reach up to tens of volts. Thus, the current-mode based waveform generator is much simpler to be turned into high-voltage application. Main issue to be ensured is high-voltage tolerant current mirrors and output capacitors.

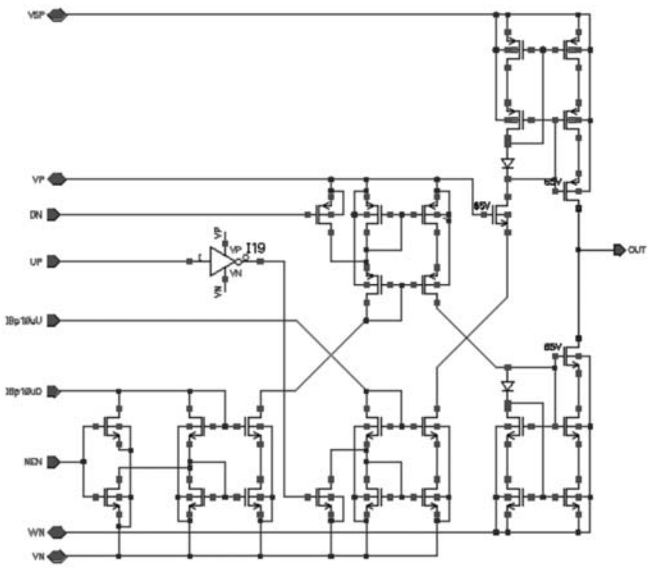

Fig. 11. High-voltage version of current-controlled waveform generator.

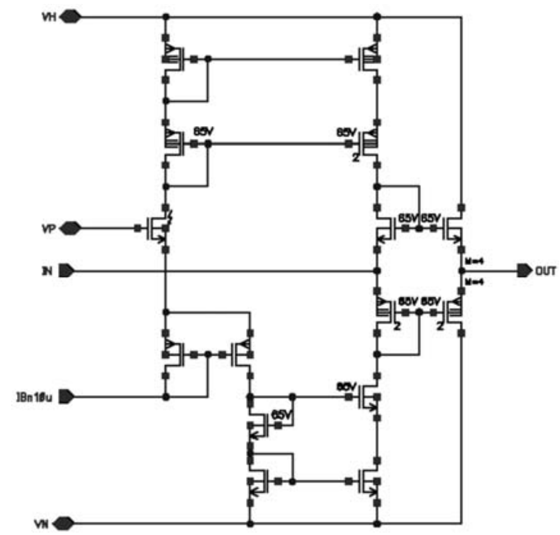

Fig. 12. Exemplary high-voltage buffer applicable as virtual supply source.

Fig. 11 shows structure of high-voltage version of trapezoidal waveform generator. There are additional HV MOS transistors at outputs of some current mirrors. They both buffer low-voltage based current mirrors from excessive voltage swing and, which is just a side-effect of their presence, maximize output impedance of current mirrors. This is very good coincidence, as voltage level at output of HV generator can swing up to tens of volts and any additional stabilization of current value against a voltage drop is appreciated for keeping quality of the final HV waveform.

The output stage of high-voltage generator can also be powered from virtual supply and ground levels. Because of a limited and predictable load imposed on virtual power modules, they can be implemented in form of a HV voltage buffer (Fig. 12) with a properly sized output stage.

Another change in the circuitry is the output capacitor. It is a stacked structure tolerant to HV range of voltage swing. If in a utilized technology process there are no good quality HV capacitors accessible, either an external capacitor can be utilized, or a more complex capacitor structure must be used. It is possible to use some of low-voltage (LV) capacitors in HV space. They can be connected in a 1-D ladder or even better a 2-D matrix, to cope with high voltage swings. Because components of such complex structure are not immune against excessive voltage, a capacitor interconnection layout must assure safe operation conditions. For example, a value maximum possible supply voltage peaks must be foreseen when deciding number of stacked LV devices.

Also, a fabrication process induced variation of capacitor values in a group of interconnected devices must be taken into account because it can cause an uneven voltage division between ladder-connected capacitors and might lead to a slightly excessive voltage drops on capacitors that happen to have smaller capacitance.

Such weak points may reduce lifetime of the generator and thus of whole IC structure. Thus, it is good to combine LV capacitors into a 2-D matrix. If the capacitors are properly connected, there is limited risk of whole row of capacitors having significantly smaller overall capacitance then other rows of capacitors. Comparison of waveform slew-rate stability for generator with single HV capacitor versus version with ladder of LV capacitors is presented in Fig. 13. Low-voltage solution shows better signal quality, but for the price of more complicated capacitor structure.

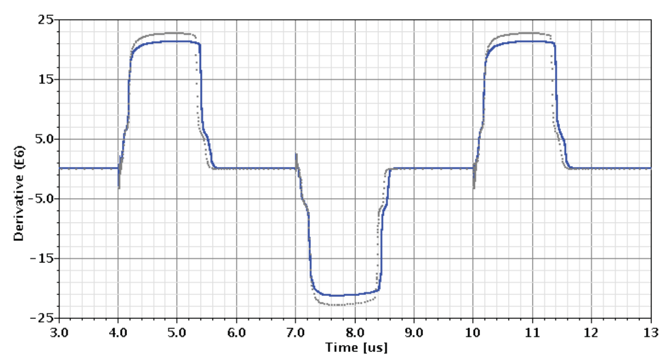

Fig. 13. Waveform derivatives of two waveform produces by HV generators equipped with different capacitors set to same value: dotted high-voltage capacitor, solid ladder of low-voltage capacitors.

V. Current-flow Control Modifications

Because Presented versions of waveform generator are equipped with current control switches placed before the output mirror stage. Usually such solution is not a problem, but specially in case of HV implementations there is possibility of a non-zero current flow in the output mirror expected to be switched off. It is so, because the current mirrors are in fact not firmly switched-off, they just conduct currents equal to zero. If any unintended current - usually a very small one - flows in current path beyond the switching point, it is transmitted to the output capacitor and can falsify final waveform parameters. Solution to this problem is simply to install a current control circuits into the output mirror stage.

Such modification must not enable any unwanted feedthrough of signals related to switch control to the output signal. Naturally, if the switches are placed before the output stage, this stage itself is not exposed to any sudden voltage changes like shortcircuits. Only current-flow changes happen.

LV waveform generator with current control switches applied to the output stage current mirrors is presented in Fig. 14. This structure is even simplified as compared to e.g. generator presented in Fig. 7. Quality of the generated waveform is comparable to previously presented LV structures.

Such modification may pose more problems in case of HV generator version. In the solution presented in Fig. 12, a current control switch is placed in the LV part of the circuitry. Now, the control information must be somehow brought to the HV output mirror. One more time the current-mode signal transmission shows its usefulness. MOS transistor is a voltage-controlled device and such is a current control transistor, no matter low- or high-voltage version.

The trick is to use a current to transfer the control signal to the HV output mirror and then a current-voltage converter to provide a voltage control signal. Simply, such converter can be implemented as a resistor (Fig. 15, left). But, if there is no precise control over a value of current used for passing control information into the HV domain, another structure is very useful.

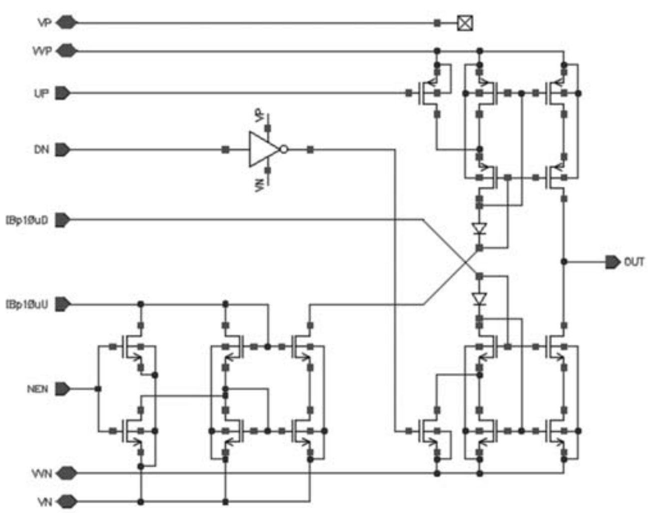

Fig. 14. Low-voltage waveform generator with current-control applied to output stage current mirrors.

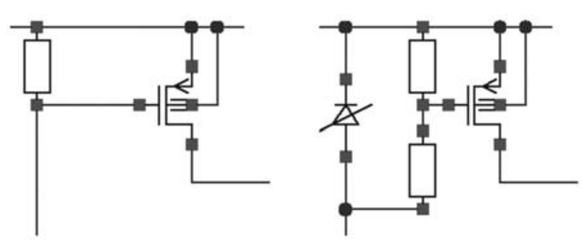

Fig. 15. Current-voltage converters for high-voltage current control: left – resistor based solution, right – voltage divider bypassed by Zener diode.

Usually Zener diodes are used as safety devices. Here a Zener diode can serve as a control voltage stabilizer. In the utilized IC process the safe gate-source voltage for most of MOS devices is limited to 5V, and maximum allowed voltage is equal 5.5V. Zener diode opens at about 6.2V, which is too high for MOS transistor control. Solution is to use a resistor-based voltage divider bypassed with a Zener diode (Fig. 15, right).

Resistor values are chosen to always ensure a voltage drop larger than opening voltage for the the Zener diode. Owing to this, Zener diode opens and stabilizes voltage drop over the resistor voltage divider at 6.2V. The voltage divider itself produces its output voltage close to 5V, which is a proper voltage level for driving the current control transistor. Output voltage of the divider can be precisely defined, because it is proportional to a resistance ratio, and not a resistance itself.

In many applications such a solution makes it possible to use an auxiliary copy of the very slew-rate coding DC current to pass the switch control signal to the HV part of the generator output stage. This slew-rate coding current is now cut-off in the HV part of the circuitry, so is always accessible in LV part of the circuitry. Value of the slew-rate coding current may change, but it is just enough to keep the copied value high enough to make the Zener diode open. Practically, it is not required to use a high current flow, it is better to use high value resistance in the HV output mirror. If there is a highly resistive polysilicon layer in utilized technology process, such resistors are not big structures. Fig. 16 presents a structure of high-voltage generator that utilizes both current-mode of control information transfer into the HV range and uses a copy of the slew-rate coding current for passing control information. Its great virtue is simplicity of internal structure. Quality of operation is very similar as in case of previous circuitry.

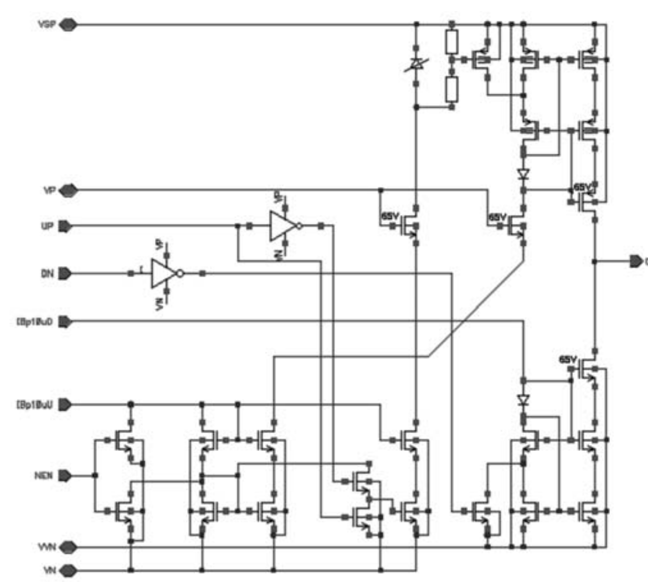

Fig. 16. High-voltage waveform with current-control applied to output stage current mirrors and copy of slew-rate control used for passing control information into high-voltage range.

VI. Conclusion

The The utilization of the current-mode based approach to a trapezoidal waveform generation has been presented. Presented generator design approach shows simplicity of a structure and an ability of efficient control over parameters of the output waveform.

The internally generated way of a digital control signal transmission into the high-voltage range makes the presented circuitry externally compatible with low-voltage control subcircuits.

The ability of straightforward and efficient adaptation to use in high-voltage applications is an important asset. Presented waveform generators can be utilized in wide range of systems, retaining a consistent structure over various applications.

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