Adjustable Generator of Edge-Rounded Trapezoidal Waveforms

Mariusz Jankowski and Grzegorz Jabłoński

Abstract—An approach to design a trapezoidal waveform generator with edge-rounding functionality is presented. The paper describes circuit able to produce edge-rounded trapezoidal waveform. Adjustment of numerous waveform parameters is possible. The signal path inside the circuit is very short. Most of circuitry required for waveform edge-rounding and adjustment is placed outside the signal path and works in DC mode.

Keywords—trapezoidal waveform generation, edge-rounding, signal shaping, harmonics reduction.

I. Introduction

NOWADAYS, wireless signal transmission becomes a dominant way of information transmission and exchange. Both analog and digital data can be transmitted this way. Digital waveforms as such are not well suited for direct wireless transmission. Sending a square wave to an antenna is not a good idea, as it introduces many high frequency harmonics. An opposite approach is based on sending digital signals as sine waves, which usually demands some kind of extra coding for providing means of information decoding at a receiver side. If there is no need or possibility for such additional coding, some intermediate form of waveform properties can be useful for wireless transmission of digital data.

Trapezoidal waveform is such kind of an intermediate signal. Most of its spectrum is located in a low frequency range. Though, there are sharp edges in this kind of waveforms. This effect still produces some amount of high-frequency harmonics. If their levels are found excessive for imposed circuit operation conditions, further waveform processing is required. Such process can be referred to as an "edge rounding". It is expected only to affect parts of trapezoidal waveforms, in which sharp edges are present. Other parts of the processed waveform should remain unmodified. Too much rounding could finally lead to a sine-like waveform and that could make the receiving and interpreting of the signal unnecessarily troublesome.

All simulations discussed in the paper are made using $0.8\,\mu m$ SOI BICMOS process, with EKV device models. All circuits are powered with $5\,V$ supply voltage.

II. Trapezoidal Waveform Generation

Well defined edge-rounded trapezoidal waveform should provide constant slew-rate for a possibly large waveform volt-

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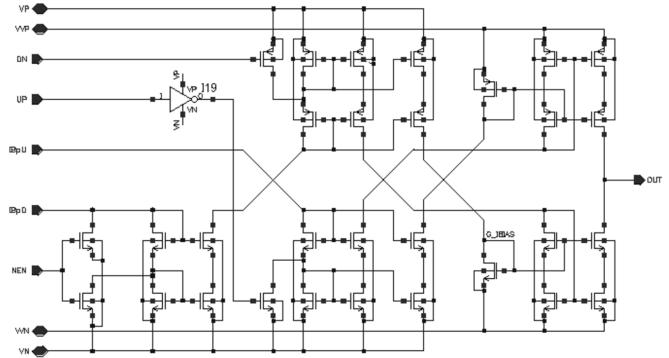

Fig. 1.   Current-controlled waveform generator.

age range, while waveform edges present for extreme waveform voltages should be rounded leaving waveform voltage-span unchanged.

Rounded trapezoidal waveform needs usually a two-stage signal generation and processing circuitry. First, the trapezoidal waveform itself must be delivered, and then it can be processed to obtain an edge-rounded shape.

There are several ways of trapezoidal waveform generation. They enable various possibilities of control of output waveform parameters [1], [2]. In presented solution a current-controlled waveform generator is introduced. Its schematic is shown in Fig. 1. It is controlled by both digital and current-mode analog inputs. The digital input signal provides data to be turned into the output waveform and then transmitted. Analog inputs are DC currents, which decide slew-rate values of the resulting waveform [3].

Generation of trapezoidal waveforms is performed by means of consecutive charging and discharging of a capacitor placed at the output of the generator. This operation principle is very simple and general. As such it can be realized even with use of a transconductance amplifier like the one presented in a handbook [4]. Though not optimal, it still offers sufficient control over shape of the generated waveform. Some circuits that contain similar generator solutions and operation principles have been even patented [5].

Control over dynamic parameters by means of DC current is possible, because waveform itself is produced by consecutive processes of charging and discharging of capacitor placed at the output of the generator. Current flow defines the amount of charge collected in the capacitor over time, charge collection on capacitor means voltage change between the capacitor terminals. Process of charging a capacitor with a DC current produces a constant slew-rate voltage signal. The output wave-
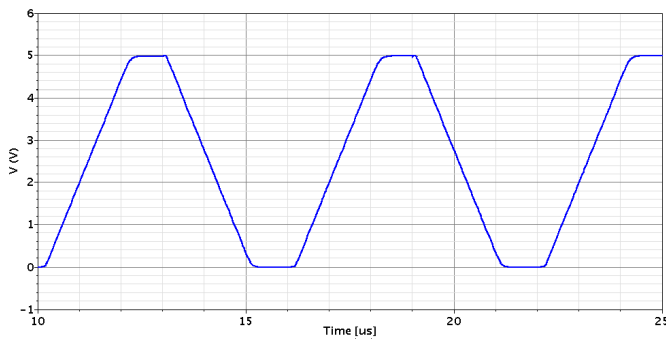
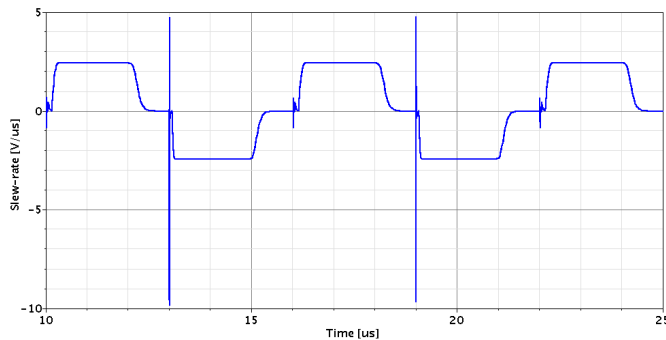Fig. 2.   Output waveform of current-controlled generator.

Fig. 3.   Derivative of waveform produced by current-controlled generator.

form of the generator is presented in Fig. 2. Fig. 3 shows first derivative of the output waveform, which is equivalent to the slew-rate value.

The output waveforms can reach from rail to rail, owing to construction of the output stage. Capacitor charging/discharging process stops if the output voltage approaches the supply level of the current mirrors of the generator, which causes outputs of these mirrors to self-extinguish themselves. It happens due to difference between their output voltages and relevant supply level too low to keep mirror transistors in proper operation modes.

Often voltage-range of the output waveform needs to be limited. Voltage range limitation can be obtained in various ways. First, output current mirrors can be powered by virtual ground and supply sources set at required limit. In such configuration, output current mirrors self-extinguish themselves for output voltage reaching required waveform limit levels.

Another way of voltage-range control is application of some additional control circuitry testing the output voltage level and switching off the output stage mirrors when the voltage limit condition is met. In a presented circuit none of these solutions is used. In fact, rail-to-rail voltage-range of the output waveform makes signal rounding procedures simpler.

III. WAVEFORM EDGE-ROUNDING

Several edge-rounding structures are proposed. They use quite different approaches to the problem. Some of them require modification of a waveform generator itself, e.g. to enable additional control over currents used for charging and discharging its output capacitor, in case of current-controlled
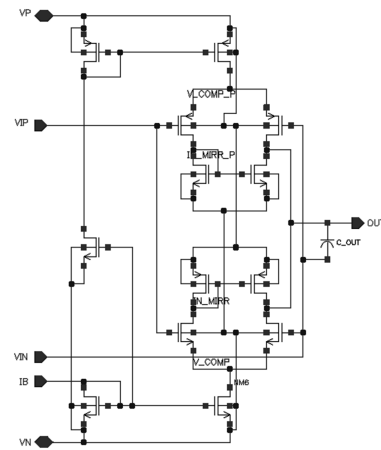

Fig. 4.   Edge-rounding circuitry presented in [3].

generators [5]. A different approach is to leave the generator intact and perform a signal rounding process as a separate stage of trapezoidal waveform processing.

A. Exemplary Solution Based on Excessive Voltage-Range Waveform

An interesting signal rounding circuitry, based on processing of excessive voltage-range waveform, is presented in [4]. The edge-rounding effect is a by-product of voltage buffer limitations. The first stage of this solution is a waveform generator, the second stage, presented in Fig. 4 serves as: a voltage buffer, a voltage range limiter, and an edge-rounding circuitry. Though it provides a whole variety of functionality, it is just a kind of combination of two simple one-stage complementary operational amplifiers that together form a pseudo rail-to-rail OPAMP, working as non-inverting voltage buffer.

This complementary OPAMP is powered with virtual supply and ground sources. Owing to this, its input signal voltage-range exceeds both its ground and supply sources. When input voltage approaches virtual power level, some internals of this OPAMP start to switch off and thus the output signal stops following the input signal. As the input voltage reaches and passes virtual power level, this effect gets more pronounced.

For a significant input voltage level excess, the output voltage finally reaches virtual power level and stays at this level. When the input voltage returns to the range between virtual supply and ground levels the output voltage leaves the limit level and starts to approach and then follow the input signal voltage.

Thus, the output signal is kept between virtual supply levels and is rounded for voltages close to these virtual supply levels. This solution is simple, but it has one drawback. When the input voltage returns into the voltage range proper for the complementary OPAMP, the previously inactive simple OPAMP switches on, and this process produces distortions of the output signal, which can be observed in Fig. 5. This figure presents a derivative of the output waveform. Some degree of slew-rate distortion can be observed. Unfortunately, the faster the processed signal, the more pronounced this phenomenon
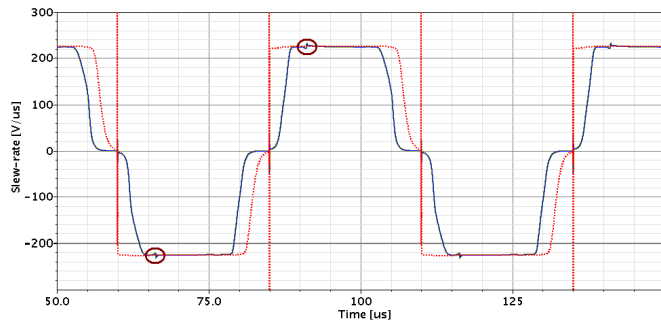
Fig. 5. Distortions imposed on output (dark one) waveform by edge-rounding circuitry presented in [3].

becomes. Possible deterioration of high-frequency signals is obviously a drawback in case of many practical applications.

B. Proposed Solution Based on Excessive Voltage-Range Waveform

Solution presented in this paper also uses excessive voltage-range waveforms to produce edge-rounding effect, but is free from signal quality limitations caused by the edge-rounding circuitry.

Fig. 6 shows the rounding circuitry with the trapezoidal waveform generator itself. The presented circuitry consists of two main parts. The first part is a very short signal path composed of excessive voltage-range waveform generator and an edge-rounding circuitry.

The latter part is a set of operational amplifiers which define and provide voltage levels and virtual power sources crucial for proper circuit operation. This part is most complicated but is placed outside the signal path. This is a big asset, the signal path-related circuitry is just provided with DC voltages produced by the off-path circuitry.

The set of input signals contains the upper and lower voltage limit for both original and rounded waveform, as well as a digital data line to be put into a trapezoidal waveform, due to application requirements. Possibility of adjustment of differences between voltage limits of original and rounded waveform enables control over rounding process. The higher are these voltage differences, the more pronounced is the effect of rounding process.

The idea of signal rounding used in the circuitry is as follows: a voltage buffer is connected to the output of the waveform generator. There is an edge-rounding device connected to it, consisting of a resistor and two diodes. The other terminals of these diodes are connected to auxiliary voltage sources, generated inside the off-path circuitry. Both diodes are connected in a way that makes them reverse biased for most of the final waveform voltage range, except for most extreme voltages. For these extreme voltages, the diodes (one at a time) start conducting and current starts flowing through resistor and this forward-biased diode.

The output signal is taken from a connection point between the resistor and diodes. A kind of highly nonlinear voltage divider is thus established. Diode is a highly nonlinear device, as for voltage drop versus current flow through the diode. So,
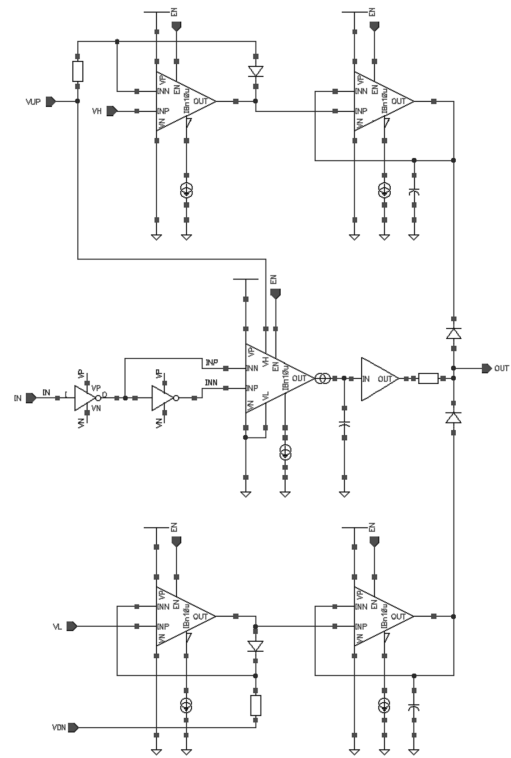

Fig. 6. Edge-rounding circuitry presented in this paper.

when a diode turns on, the input voltage becomes scaled on the resistor-diode voltage dividers in increasingly nonlinear manner. This nonlinearity causes the output signal shape to get rounded. When the original waveform voltage leaves the limit voltage area, the output signals become less and less rounded and when the relevant diode turns off, the output waveform starts to follow the original waveform voltage level.

The issue still to solve is control over voltage range of the output voltage. In order to produce edge-rounded waveform having specific voltage range, it is necessary to provide two auxiliary supply sources inside this voltage range. The original trapezoidal waveform becomes rounded when one of rounding diodes switches on. According to this, the auxiliary voltage levels differ from the final waveform voltage limits (and are more centrally placed in voltage-range) voltage drop on the rounding diodes. The problem is that this voltage drop depends on current flowing through the diode. It is required to make this current value known before it is produced in the rounding resistor-diode divider.

A solution to this issue is knowledge of a voltage drop on the divider resistor. Original waveform is input to one terminal of this resistor, while rounded waveform is generated at its other terminal. Because of connection mode of the resistor and the conducting diode, the same current passes through both these devices. The way of finding auxiliary voltages is to recreate voltage drop that occurs on each of the rounding diodes for extreme waveform voltage values. It is realized with use of recreated current flow through a known divider resistor connected to known voltage limits of original and rounded waveforms.
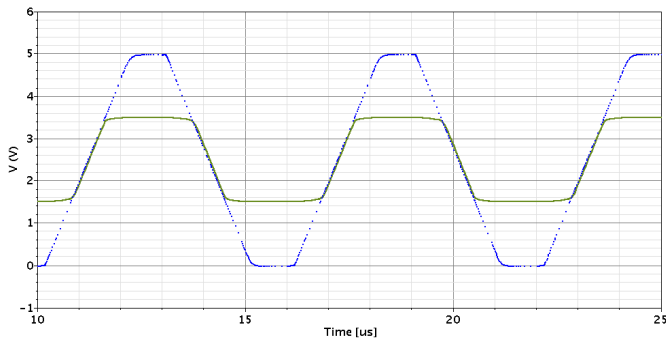
Fig. 7.   Original (dotted) and rounded (solid) waveforms.

Fig. 9.   Comparison of rounded waveforms generated with various overshoots of input waveform, lines: solid 1.5 V, dashed 1.0 V, dotted 0.5 V overshoot.
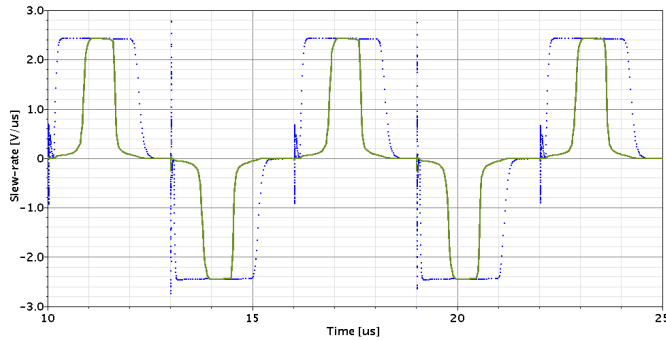

Fig. 8.   Derivatives of original (dotted) and rounded (solid) waveforms.

For upper part of waveform this task is fulfilled with the application of OPAMPs placed in upper part of the Fig. 6. The upper left OPAMP generates upper auxiliary voltage level for the rounding circuitry. This OPAMP works in configuration similar to that of non-inverting amplifier, but with an auxiliary diode in the feedback loop. A cathode terminal of this diode is connected to the inverting input of this upper-left OPAMP, and the anode terminal is connected to the output of this OPAMP. This diode is identical as the diodes in the rounding circuitry.

An auxiliary resistor, identical to the one in the rounding circuitry, is connected between an inverting input of this upper-left OPAMP, and upper voltage level of the original waveform. The non-inverting input (and so the inverting input) of the OPAMP is set to equal to the upper limit voltage of the output waveform. As there is voltage drop on this resistor, current flow through the resistor is forced. The only way for this current to flow is from the OPAMP output and through the auxiliary diode in the feedback loop. The OPAMP output can adjust its output voltage level so as to cope with the voltage drop on the diode and still keep unchanged voltage on its inverting input.

The current flowing through this auxiliary resistor is equal to the maximum current flowing through the rounding resistor and the active diode. Because all this current is forced to flow through the auxiliary diode, the voltage drop on this diode is equal to the maximum voltage drop on an identical rounding diode. That means that voltage on this OPAMP output is equal to the required upper auxiliary voltage. The upper right OPAMP in Fig. 6 serves as a voltage buffer and provides the generated auxiliary voltage to the rounding circuitry. Lower
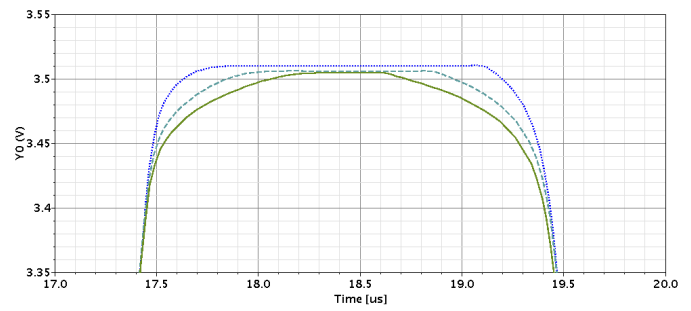
auxiliary voltage level for the rounding circuitry is generated in analog manner, by OPAMPs placed in the lower part of schematic in Fig. 6.

The original and rounded waveforms are presented together in Fig. 7. A precise voltage-range limitation can be observed. A difference between required and obtained limit voltage levels of the rounded waveform are of order of single millivolts. This difference is related to non-idealities of OPAMPs used in the design and are closely related to the offset voltages in their differential pairs.

The derivatives of the original and the rounded waveforms are presented together in Fig. 8. It can be seen that the slew-rate of the rounded waveform changes in a less abrupt manner.

Comparison of rounded waveform having same voltage-range limits but generated with various overshoot voltages (differences between original and rounded waveform voltage limits) is presented in Fig. 9. It is clearly visible that changing the overshoot voltage enable control over intensity of the edge-rounding process.

C. Simplification of the Proposed Solution

In presented solution a voltage buffer is present between the original waveform generator and the rounding circuitry. It secures a non-distorted process of charge collection on the generator output capacitor.

On the other hand, it should be a kind of rail-to-rail device, able to pass even rail-to-rail waveforms produced by the preceding generator. Such buffer circuitry is more complicated than simple OPAMPs. Avoiding design and placement of such a signal processing module could save some chip area and could lower power consumption. Such a rail-to-rail buffer can also be a source of signal quality deterioration itself.

Indeed, it can be shown that this buffer can be removed with very limited consequences for the quality of the circuit operation. If there is no voltage buffer the current flowing through the rounding circuit is subtracted from the current that charges/discharges the capacitor at the output of the generator. Such behavior distorts the output signal, but this effect occurs in the voltage-range for which the output waveform is expected to be rounded. Usually there is no detailed requirement on shape of rounded signal; rather a degree or effectiveness of this process is what counts. The conclusion then is that the described distortion can be treated just as slight change of rounded waveform shape.
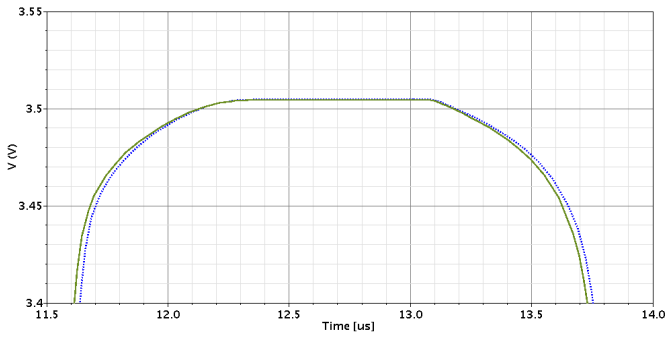
Fig. 10. Comparison of zoomed-in output waveforms produced by circuit with (dotted line) and without (solid line) voltage buffer.
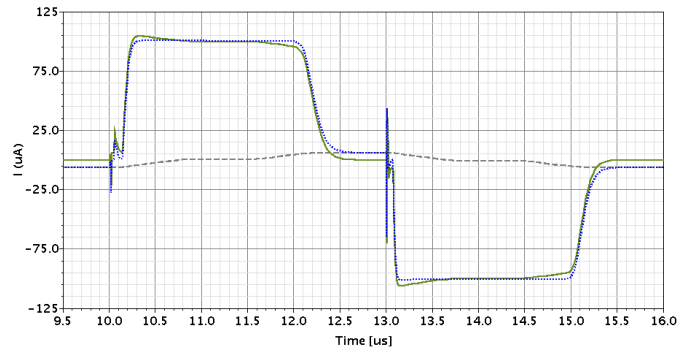

Fig. 11. Currents related to output stage of the circuit without voltage buffer: current flow from the generator (dotted), current flow to the output capacitor (solid), current flow to the edge-rounding circuitry (dashed).
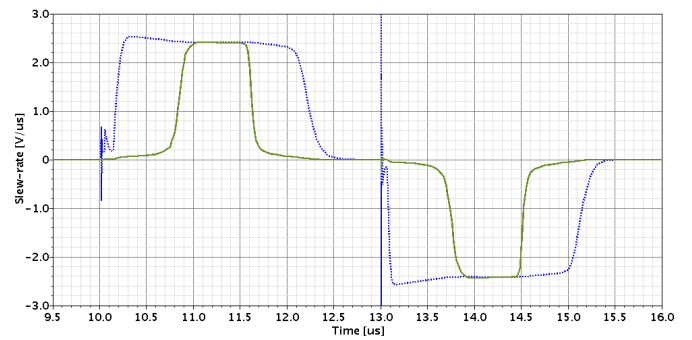

Fig. 12. Derivatives of excessive waveforms produced by generator only (dotted line) and of voltage-limited waveform by generator with edge-rounding circuitry and without any output buffer (solid line).

A deeper insight into circuit operation shows, that when original waveform voltage approaches its limit level, a current from the generator decreases due to self-extinguishment process. But on the contrary to a normal operation with a buffer on the generator output, it does not completely stop to flow. It happens because the rounding circuitry sources/sinks its own current to the output of the generator and this current flows into the output of the waveform generator and makes the active output stage current mirror pass it to the relevant power net.

By the way, this power net voltage is equal to the voltage limit of the original waveform. A kind of side effect is that current flow through the output stage of current mirrors inside the generator keeps voltage level at the output of the relevant current mirror – and thus output voltage of the generator itself – slightly different from the required voltage limit value for the original waveform. The original waveform voltage-range becomes slightly reduced as compared to the expected one. According to simulation results, this reduction can reach up to a few tens of millivolts (Fig. 10).

Another phenomenon related to removal of the voltage buffer happens when there is a change of active output stage current mirror in the generator and the original waveform starts leaving the limit voltage. The current mirror, that so far was enabling current flow through the rounding circuitry, goes off and cannot pass any current. Current of the newly activated current mirror flows in the opposite direction and also cannot support the current flow through the rounding circuitry.

The only source/sink of this current is now the output capacitor. The effect is that now the rounding circuitry charges/discharges the output capacitor in same way as the active current mirror in the output stage of the generator. This behavior is shown in Fig. 11. As a result, the voltage change at the output capacitor is faster than expected, which also can be observed in Fig. 10. Again, this phenomenon takes place only, when the rounding circuitry is active and causes only slight change of the rounded waveform.

As discussed, change of the original waveform takes place only for the parts of this waveform which become significantly reshaped by the rounding circuitry (Fig. 12). Due to highly nonlinear nature of this process, the original waveform becomes suppressed and squeezed into voltage-range of the rounded waveform.

Thus, all the signal shape alterations also become sup-

pressed and affect the rounded waveform only through a slightly modified shape of the rounded parts of this waveform, which can be seen in derivatives of output waveforms of both circuit versions, with and without the voltage buffer (Fig. 13). The voltage-range of non-affected constant slew-rate part of the rounded waveform is identical as in case of circuit version with voltage buffer present between original waveform generator and the rounding circuitry.

Fig. 14 present derivatives of original and output waveforms of the edge-rounding circuitry without any voltage-buffer. Both waveforms have the same voltage-range limits and slew-rate values. It can be observed that the derivative of the rounded waveform is much smoother than the one of the original
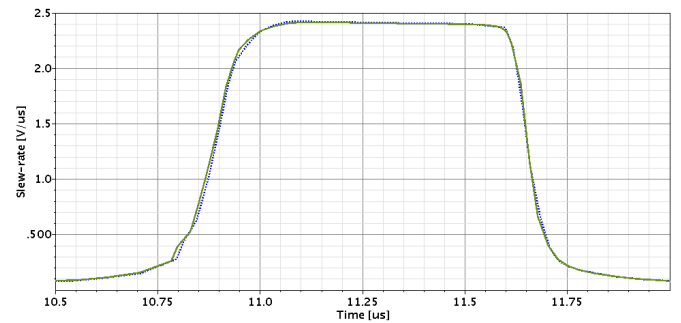

Fig. 13. Derivatives of output waveforms produced by edge-rounding circuit with (dotted line) and without (solid line) a voltage buffer.
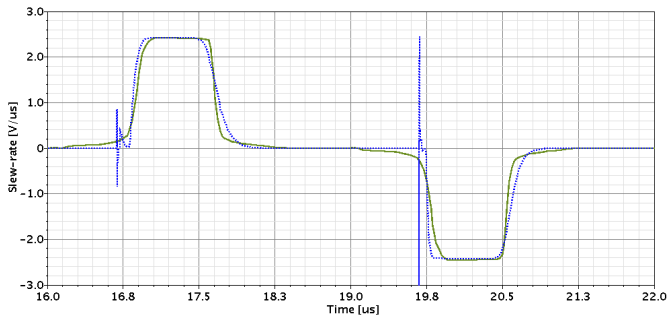
Fig. 14. Derivatives of waveforms produced by generator only (dotted line) and generator along with edge-rounding circuitry (solid line).
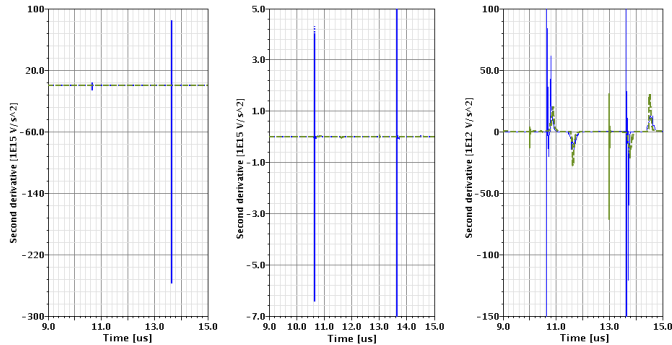

Fig. 15. Second derivatives of waveforms produces by generator only (solid line) and generator along with edge-rounding circuitry (dashed line).

Fig. 16. Comparison of DFT of waveforms produces by generator only (left) and generator along with edge-rounding circuitry (right).

IV. CONCLUSION

Presented circuitry offers an effective way of rounding of trapezoidal waveforms. The voltage-range of the output waveform and degree of signal rounding can be adjusted according to requirements. The main virtue of the circuitry is an extremely short signal-path beyond output of the waveform generator itself.

The presented rounding circuitry is able to work with un-buffered output of current-mode output of generator. Such simplification causes only slight influence, but not deterioration, of the output waveform quality.

The edge-rounding circuitry is presented in the paper as a part of a whole signal generation system with the current-controlled waveform generator. Though, it can process waveforms produced by various generators. Moreover, because of a very simple structure of the edge-rounding module, it is possible to design a high-voltage equivalent of the presented circuitry.

waveform. All glitches visible for the waveform produced by the generator only (Fig. 3, 14), are removed during the edge-rounding process.

A kind of measure used for assessment of presence and influence of high-frequency harmonics is second derivative of output waveform. Higher value of second derivative means quicker change of signal speed, which in turn means more high-frequency harmonics, as they are needed to produce such peaks in waveforms.

Fig. 15 shows second derivatives of the waveforms produced by the generator only, and by the generator with the edge-rounding circuitry. Both waveforms have the same voltage-range limits and slew-rate values. High-value second derivatives are present in case of waveform-only solution. All these high-value glitches are extinguished owing to way of the edge-rounding circuitry operation.

An overview of frequency domain properties of waveforms generated by the generator only and the generator followed by the edge-rounding circuitry are presented in Fig. 16. Reduction of high-frequency harmonics is a visible consequence of edge-rounded shape of the output waveform.
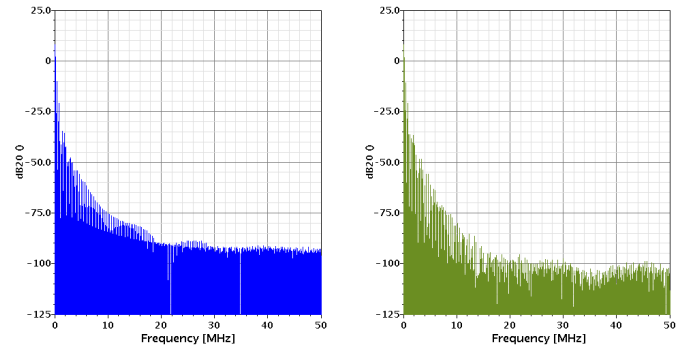
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