Investigation, Analysis and Evaluation of a Riemann Pump in GaN Technology

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***Abstract*—A novel architecture for a digital-to-analog converter is investigated which improves the signal-to-noise ratio of conventional converter concepts. The presented concept has resulted in an arbitrary waveform generator which is capable to provide several watts of output power. Further the HEMT (high electron mobility transistor) technology have made it possible to cover a baseband frequency from DC to 5 GHz, which simulations have confirmed. A highly integrated digital driver circuit in GaN (gallium nitride) technology has made it possible to process a one chip solution for the DAC with a power amplifier. The ability to steer a current out of a defined set of slopes allows to synthesize an arbitrary waveform. Measurement results have yielded a baseband frequency of 100 MHz for an input control data rate of 200 Mbps. The triangular signal proved the feasibility to generate arbitrary signal waveforms.**

***Index Terms*—AWG, DAC, transmitter architecture.**

I. Introduction

THE immense demand on high data rates leads researchers to investigate new technologies to improve conventional concepts. One concept which improves the performance is the Riemann Pump [1]. The aim to develop a Riemann Pump in GaN technology is to generate a high power modulated microwave signal with a baseband bandwidth of 6 GHz suitable for the next generation of mobile communication. The feasibility to cover the whole frequency range from DC to 6 GHz enables this architecture to operate with all common mobile communication standards. Due to the fact that the sum of several signals of the common mobile communication standard can be generated, a concurrent transmitter is built which increases the data rate up to 10 Gbps. The possibility to generate any modulated RF signal leads to a much higher data rate as with conventional concepts of RF-FE. This idea is based on software defined radios. In fact of the summation of different signals enables this technique to concurrent transmit different signals and hence increase the data rate. The advantage of GaN is to switch high powers with high frequencies as conventional CMOS switches are limited in power. As the power consumption of GaN HEMTs exceeds the limits for mobile devices the presented architecture is suitable for base station transmitters.

This paper presents the first ever built demonstrator in GaN technology with measurement results which verified the concept of a multi bit charge pump. A challenging task was to ensure the proper switching of a push pull stage with depletion mode n-transistors, as there are no complementary transistors available. A proper digital driver circuit is investigated to allow a proper switching of a depletion mode n-HEMT which source potential is not fixed to ground potential rather changing the potential. The GaN HEMTS are able to switch with a frequency of 30 GHz which results in a synthesized baseband signal frequency of 6 GHz while ensuring an oversampling of 5. Common concepts and hardware topology as CMOS are limited in switching frequency or in the power. An oversampled PCM converter improves the SNR by 5 to 7 dB for every one bit increase of resolution, . Every increase in the oversampling ratio improves the SNR by 3 dB for the conventional PCM converter. However the Riemann conversion improves the SNR by 5 to 10 dB for every bit increase of resoultion but also increase the SNR by 9 dB for every doubling of the oversampling ratio. Equation 1 illustrates the mathematical approximation for the SNR of the Riemann conversion, for further details and the derivation see [8].

$$SNR_{dB} \approx 6,02N + 9,03r - 7,78 + 10log(1 - \frac{1}{2^{N-1}} + \frac{1}{2^{2N}}) \tag{1}$$

The factor N is for the number of bits used for the resolution, while r is the exponent of the oversampling ratio which is defined as $OSR = 2^r$.

II. Concept of the Riemann Pump circuit

In this section a digital-to-analog converter (DAC) is described which is established from the concept of a charge pump. The digital-to-analog conversion is based on the current steering topology and pumps charges into a capacitive output load. As the current over time is integrated to form the resulting voltage this custom charge pump is named after the inventor of the Riemann integral, Bernhard Riemann. This technique

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made it possible to synthesize arbitrary signal waveforms by varying the current, see Equation 2.

$$V_{out} = \frac{1}{C_{out}} \int_0^t i_{out}(\tau)\, \mathrm{d}\tau. \qquad (2)$$

Absolutely essential to convert digital input data into a defined analog output signal is to establish a defined set of current amplitudes which charge and discharge the output capacitance. For a high signal integrity of the synthesized signal, a high sampling frequency as well as consistent current sources were needed. In Fig. 1(a) eight different slopes represent the change of the output voltage for a given sampling interval. These eight slopes correspond to a three bit resolution of the DAC. Figure 1(b) illustrates an example of a synthesized output signal using these slopes. The solid black line represents a former calculated desired output signal which should be synthesized using the Riemann Pump. For each sampling point the slope is chosen which minimizes the error between the sampled desired and the synthesized signal. As the eight slopes are encoded it is possible to control the output signal with a digital input stream representing the sequence of slopes to synthesize the signal.

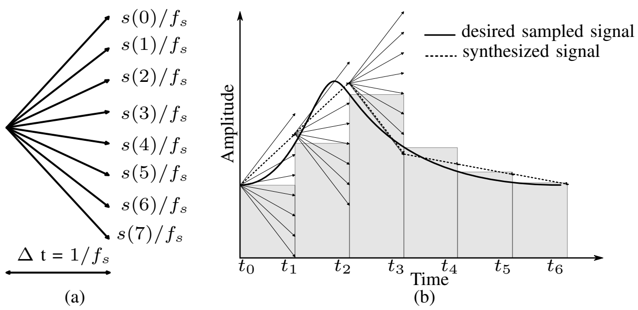

Fig. 1. (a) Representation of relative slopes and (b) signal generation with riemann code.

In order to generate these eight different currents the concept of a charge pump in a push-pull configuration is used. The pushing transistors contribute to an increase of the output signal while the pulling transistors decrease the amplitude of the output signal. Mandatory for the correct functioning of the push-pull configuration is a digital driver circuit to ensure a proper switching of the transistors connected to the top rail. Figure 2 shows the schematic of the Riemann Pump, where the single stages are cascaded in parallel. The dimension of the power transistors in parallel is increased linearly with the power of 2 to ensure the correct encryption. The digital driver circuit is marked with the dashed line and is necessary for each single stage cascaded in parallel. An implemented power amplifier, serving as the output load, makes the use of a RFFE unnecessary. This technology is capable to provide high power at high switching frequencies, which is intended to get a high sampling rate and hence a high signal integrity.

III. Implementation and Assembly of a Demonstrator

To the best of the author's knowledge, the first ever built demonstrator in GaN technology is presented. To keep the measurement complexity small, the built DAC got two bit

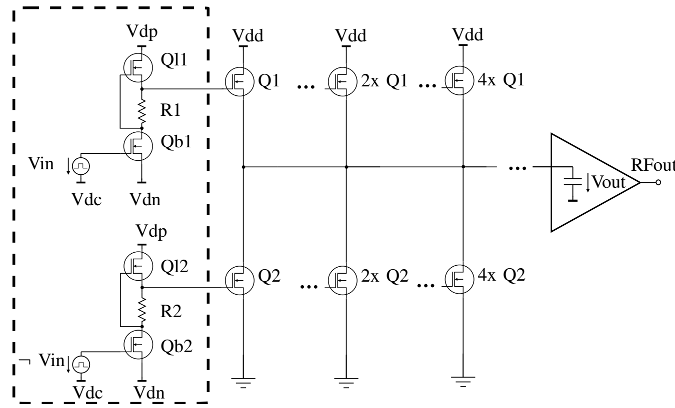

Fig. 2. Schematic of the riemann pump. Marked on the left side is the driver circuit which is necessary. The push-pull stages are/were connected in parallel.

resolution which is fine to proof the concept. For the digital switching of the GaN power transistors a monolithic microwave integrated circuit (MMIC) is used which has already implemented a proper driver circuit for the power transistors. The MMICs are designed and fabricated in the 0.25 µm AlGaN/GaN HEMT technology by Fraunhofer IAF and are of assistance in this realisation of a Riemann Pump, while the conventional application is in a Class-S amplifier [2]. Figure 3 (a) illustrates the schematic where the grey painted areas represent a single MMIC. In Fig. 3(b) the layout of the realised demonstrator is shown. The green shapes represent MIM capacitors for filtering purpose and the black ones the used MMICs. In order to reduce the impact of phase delays of the signal the input and output lines are of the same length, as well as the bond wires. The power transistors source potential of the used MMICs got a via to the backside metallisation of the MMIC, hence it was necessary to isolate this contact for the high side (pushing) transistors. This isolation is realized by an isolated pad on the substrate. The trade-off which comes with this solution is the reduced heat transfer.

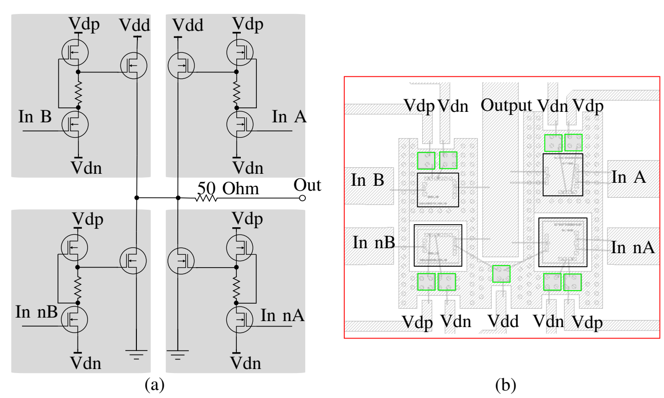

Fig. 3. (a)Schematic of assembly; grey highlighted the used MMICs. (b) Assembled demonstrator layout.

Nevertheless the first Riemann Pump in GaN technology were assembled and tested. Figure 4(a) shows a photograph of the bonded chip connection according to the layout in Fig. 3(b). This chip connection marked with the red shape is illustrated in the photograph of Fig. 4(b). The demonstrator is of the size

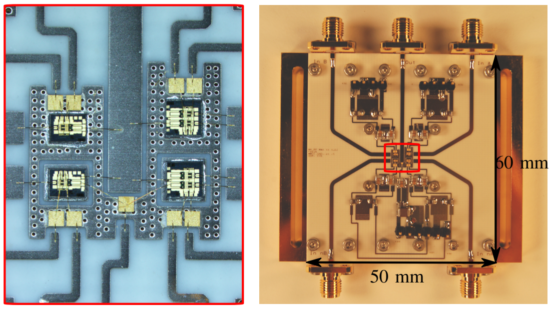

Fig. 4. (a) Chipconnection Photo, (b) realized demonstrator.

50x60 mm, has four input and one output line and in addition to the DC supply voltage connectors a decoupling network.

IV. Time domain measurement of synthesized output signal compared to simulation

To proof that the built demonstrator can convert digital input streams into an analog output signal the time domain measurement was performed. A custom control and measurement strategy was applied to get decent results. Two differential input signals, hence four signals in total, were applied by an arbitrary waveform generator (Keysight M8195A) to represent the digital data stream. These signals had to be amplified by a broadband pre-amplifier and shifted in the DC offset with bias tees to ensure proper switching of the transistors at the input. First of all a short stability check was performed to ensure that the DUT does not oscillate. Further the switches are controlled with an synchronous signal, as seen in Figure 5(a), leading to a push-pull measurement with resistive load. Hence the output signal switches between Vdd and GND as can be seen in Figure 5(b). Figure 5(a) illustrates one differential digital input

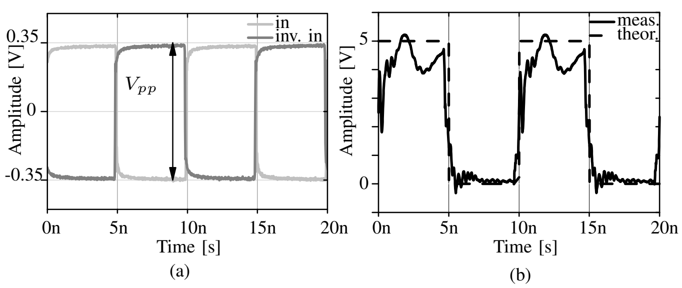

Fig. 5. (a) Differential input control signal and (b) corresponding output signal; (b.1) dashed theoretical signal, (b.2) measured signal.

stream generated by the AWG for a data rate of 200 Mbps in the time domain. Controlling the device under test, loaded with a resistor, with this signal led to the output signal in Figure 5(b). The black dashed line represents the theoretical output of an ideal switch while the grey continuous line shows the measured output signalof the DUT. To show the feasibility to synthesize different output signals the resistive load is replaced by a capacitive load. Synchronous on-switching of both pushing transistors while the pulling transistors were closed led to the expected results as already shown with the resistive load. Here the capacitor is charged with the maximum available current, hence the biggest slope is chosen. In order to select a smaller slope both pushing as well as both pulling transistors had to be switched asynchronous. The smaller slope $1i_0$ is illustrated in Figure 6(a) while the bigger slope $3i_0$ is shown in (b).

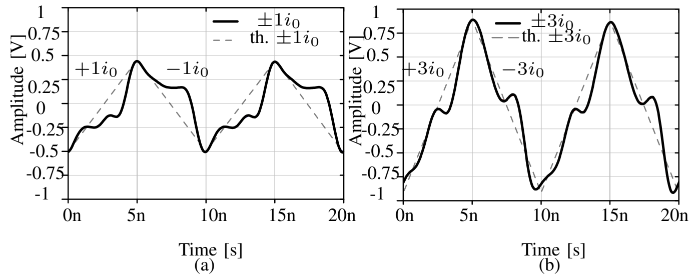

Fig. 6. Dashed line theoretical slope; solid black line measurement. Slope of (a) $\pm 1i_0$ and (b) $\pm 3i_0$.

The notation of both figures are the same, the solid black line represent the measured time domain signal for the frequency of 100 MHz, while the dashed line represent the theoretical signal waveform.

V. Conclusion

A first prototype of a Riemann Pump in GaN technology has been presented to validate the concept of this current steering topology. The measurement results have shown the feasibility of synthesizing arbitrary waveforms at 100 MHz and the potential of the chosen technology promises to cover even higher frequencies.

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