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

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***Abstract*—A novel architecture for radio-frequency digital-to-analog converters (RF DACs) is investigated that improves the signal-to-noise ratio (SNR) of conventional converter concepts. The presented concept results in an arbitrary waveform generator that is capable to provide several watts of output power. Further, the high electron mobility transistor (HEMT) technology provides high switching frequencies to ensure an oversampling ratio of 5 for a wide baseband bandwidth. The utilization of gallium nitride (GaN) enables to design a one-chip solution of a RF DAC co-integrated with a power amplifier (PA), which is named Riemann Pump. The Riemann Pump, which is controlled with a digital bit-stream, is based on the current steering topology and provides the possibility to synthesize arbitrary waveforms. A two-bit RF DAC designed with multiple monolithic microwave integrated circuits (MMICs) proofs the feasibility to generate arbitrary waveforms. Measurement results yield triangular signals with a baseband frequency of 100 MHz for an input-control data rate of 200 Mbps.**

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

I. Introduction

THE immense demand for high data rates in mobile communication leads researchers to investigate new architectures to improve the conventional concepts. One concept that 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, which is suitable for the next generation of mobile communication. The possibility to cover a frequency range from DC to 6 GHz enables this architecture to operate with all common mobile communication standards. The advantage of GaN is to switch high power at 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.

The presented concept of the Riemann Pump improves the SNR compared to conventional pulse-code modulation (PCM) converters. A PCM converter improves the SNR by 5 to 7 dB for every one-bit increase of resolution while the Riemann conversion improves it by 5 to 10 dB [2]. Every doubling of the oversampling ratio (OSR), which is defined as $\mathrm{OSR} = \frac{f_{\text{sampling}}}{2 f_{\text{signal,max}}}$, improves the SNR of a PCM converter by 3 dB while the Riemann conversion improves it by 9 dB. The mathematical approximation for the SNR of the Riemann Pump is given in Equation 1. For further details and the derivation see [2].

$$SNR_{\mathrm{dB}} \approx 6.02N + 9.03r - 7.78 + 10\log\left(1 - \frac{1}{2^{N-1}} + \frac{1}{2^{2N}}\right) \quad (1)$$

The factor N represents the number of bits used for the resolution, while r is the binary logarithm of the OSR.

This paper presents the first realization of a Riemann Pump in GaN technology with measurement results that verify the concept.

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

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

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.

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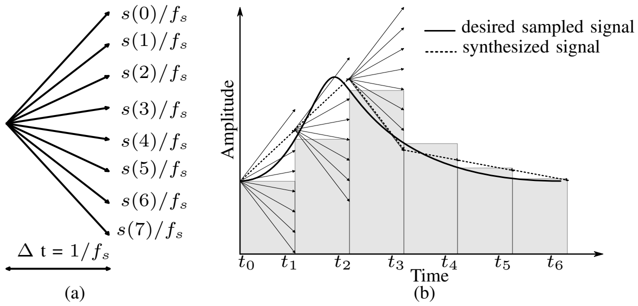


Fig. 1. (a) Representation of relative slopes and (b) signal generation with riemann code.

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

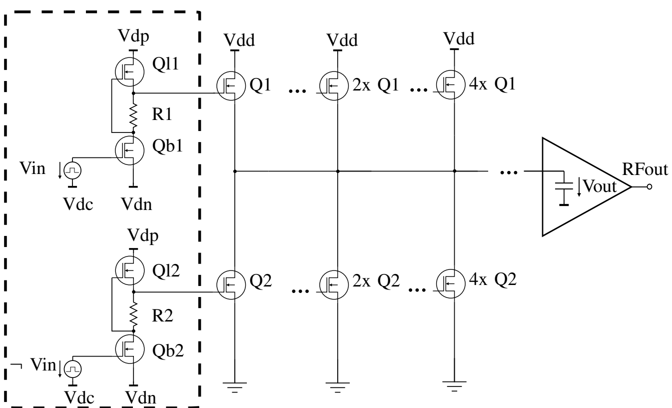


Fig. 2. Schematic of the riemann pump. Marked on the left side is the driver circuit which is necessary. The push-pull stages are/were connected in parallel.

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 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 [3]. 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

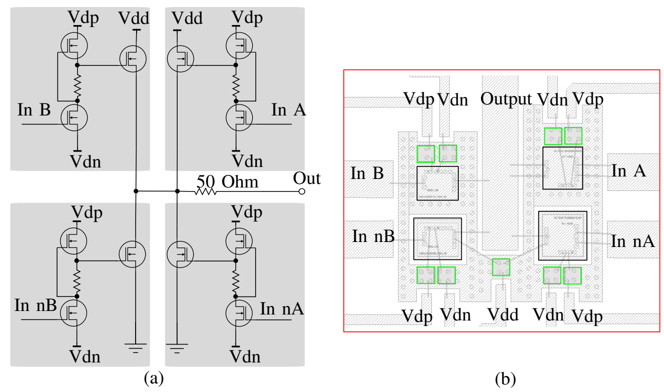
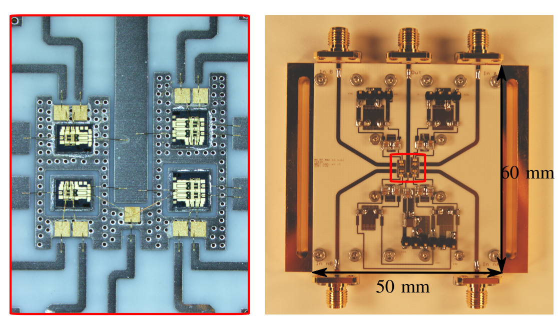


Fig. 3. (a)Schematic of assembly; grey highlighted the used MMICs. (b) Assembled demonstrator layout.

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.

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



(a) (b)

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

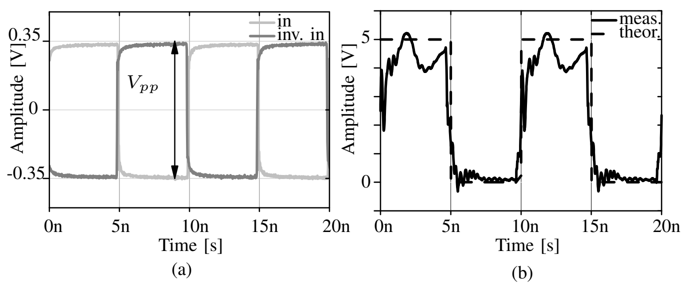


Fig. 5. (a) Differential input control signal and (b) corresponding output signal; (b.1) dashed theoretical signal, (b.2) measured signal.

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).

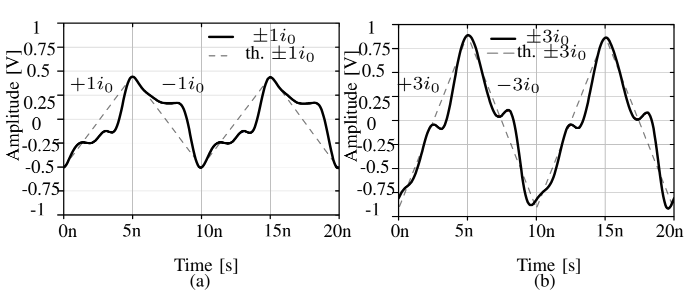


Fig. 6. Dashed line theoretical slope; solid black line measurement. Slope of (a) $\pm 1i_0$ and (b) $\pm 3i_0$.

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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