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Gallium Nitride Based High-Power Switched HIFU Pulser with Real-Time Current/Voltage Monitoring

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***Abstract*—High-Intensity Focussed Ultrasound (HIFU) techniques make use of ultrasound transducers capable of delivering high powers to be delivered at high frequencies. Real-time monitoring of power delivered can avoid damage to the transducer and injury to patients due to overexposure.**

This paper demonstrates the real-time current and voltage monitoring capabilities of a new Gallium-Nitride (GaN) based switched mode transmit pulser developed for the University of Leeds High-Intensity Focussed Ultrasound Array Research Platform (HIFUARP) system, which uses a novel approach of using an Analog Front End (AFE) floating on the transmitter output to provide high bandwidth current measurement.

I. Introduction

High-Intensity Focussed Ultrasound (HIFU) techniques make use of ultrasound transducers capable of delivering large acoustic powers to a localised tissue region to cause thermal ablation [1] or mechanical stimulus [2] [3]. Such transducers require large electrical powers (>10 W) to be delivered at high frequencies (>1 MHz) in order to generate the necessary acoustic pressures. Estimation or monitoring of power delivered is also necessary to avoid damage to the transducer [4] or to avoid injury to patients due to overexposure.

In a typical HIFU system, a linear power amplifier in conjunction with a signal generator will be used to drive the transducer. Such systems provide the necessary amplitude and phase control whilst minimising harmonic distortion. However such systems are expensive, physically large [5], and suffer from poor electrical efficiency. This is especially problematic as the move towards multiple element transducers [6] to facilitate techniques such as beam steering and dynamic focus.

As an alternative to linear amplifiers, multi-level switched circuitry can be used to drive HIFU transducers. Such circuits provide reduced size, lower cost, and higher efficiency that linear amplifiers [7] [8]. Switched circuits use a series of discrete voltage levels to approximate an an analog waveform using a stepped waveform. As a consequence however the waveforms generated by such circuits introduce unwanted harmonics causing large acoustic powers at the third and fifth harmonic in particular [9]. As typical HIFU transducers are particularly resonant at these harmonics [10] [11], these harmonics will be converted into acoustic power.

II. Switched-Mode Transmit Pulsers

The harmonic output of switched pulsers can be reduced through careful design of the transmit waveforms. The use of a Harmonic-Reduction Pulse-Width Modulation (HRPWM) technique [12] [13] [14] has been previously shown to allow partial cancellation of the third and fifth harmonics across multiple amplitudes. This has been demonstrated previously for HIFU applications [15].

Switched-mode transmit pulsers are limited however in drive frequency capabilities due to the need of a large drive bandwidth to produce the necessary rise times to generate switched waveforms, especially at the high powers required for HIFU applications. The maximum frequency of the pulsers is limited by the switching speed of the transistors (particularly turn-on/turn-off times), and by their thermal capabilities as the dynamic power dissipation of the devices increases with frequency.

The previously demonstrated University of Leeds (UoL) High-Intensity Focussed Ultrasound Array Research Platform (HIFUARP) system [15] makes use of a P-Channel MOSFETs (PMOS)/N-Channel MOSFETs (NMOS) topology that is capable of switching at around 1.1 MHz albeit with limited potential of amplitude control due to the rise/fall times of the transistors. A method to improve the amplitude control using a Modified Harmonic-Reduction Pulse-Width Modulation (mHRPWM) scheme have been shown [16] that attempts to maximise control performance. Much of the performance limitations of the HIFUARP card come from speed limitations of PMOS transistors.

It is possible to increase the performance of switched pulsers by eliminating the PMOS transistors, opting for an all NMOS topology. However this requires redesigning the topology as PMOS and NMOS transistors are not directly interchangeable. By switching to an all-N topology it is possible to then switch to faster transistor technology such as Silicon-Carbide (SiC) or Gallium-Nitride (GaN) devices.

III. Power Measurement

In order to monitor the power delivered by the therapy transducer, it is necessary to monitor the output either in the acoustic domain or in the electrical domain. This is typically achieved by simply estimating the power based on scaled radiation force balance measurements of the transducer output [17]. An alternate approach is to measure both current and voltage of the output of the drive waveform in real time to directly calculate power delivered in order to achieve a more accurate calculation of power delivered [18].

Measuring the current in real time requires some form of current sense circuitry. In order to allow the use of multiple transducer elements, it is necessary for the current sensing to be performed on the high-side of the output as the transducer elements typically share a common ground. This means that isolated measurement techniques are required. This would typically be performed by the use of either inductive isolation such as current transformers, Hall Effect sensors, and Ragowski coils, or using Current Shunt techniques.

Current sense transformers are placed in series with the output meaning that they must be capable of handing the full output current to the load, which is impractical for high current/high frequency. Hall effect sensors provide an alternative to transformers by measuring the magnetic fields produced by current flowing through a wire which means they do not need to be placed in series with the output, but are limited in the frequency measurement to typically sub-MHz. Ragowski coil circuits use the output trace itself for the sensor so do not affect power handling, and have been shown to provide high current and frequency capability [19], but are difficult to implement in practice.

Typical current shunt techniques may use amplifiers with a wide voltage input to allow non-isolated direct measurement of the voltage across the current shunt, however such amplifiers are usually limited to around 50 V offsets which are insufficient for the >200 Vpp outputs used for driving HIFU transducers. Alternatively the use of an isolated analog amplifier is possible to directly transfer the analog signal across an isolation barrier, however such amplifiers suffer from limited bandwidth (<1 MHz).

IV. GaN Transmitter with Current/Voltage Sense

An experimental transmit pulser architecture has been designed using GaN transistor technology that allows for multi-level (5-level in the current design) switched waveforms to be generated at high frequencies (up to 5 MHz) whilst delivering large electrical powers. The design is nominally rated for output voltages up to 600 Vpp output at up to 800 W Root-Mean-Square (RMS) output at 1.1 MHz for short bursts, and for 200 W RMS at 1.1 MHz Continuous Wave (CW). The output power handling scales roughly inversely with increasing frequency due to cooling limitations. The architecture of this pulser is not presented in this paper.

The card also includes real-time Current and Voltage monitoring circuitry to measure the electrical output power of the pulser into the attached load. A block diagram of the circuitry is shown in Fig. 1(a). The voltage sense circuit consists of a resistive sense element, followed by a differential amplifier circuit with integrated 5MHz Low-Pass Filter (LPF) (Analog Devices LT6600CS8-5), and switchable gain resistor circuit for changing between two different amplification levels, and finally an 8-bit Analog to Digital Converter (ADC) (Analog Devices AD9283) is used to digitise the signal.

An additional step is added using a Serialiser-Deserialiser (SERDES) chip (Texas Instruments SN65LVDS315) to convert the parallel ADC output to a single bit serial data stream. The SERDES chip used for this circuit is typically intended for interfacing cameras to a CSI (Camera-Serial-Interface) bus, however by configuring the device to run without an image length validation, it is possible to use it as a low-part-count general purpose 8-bit serialiser. Deserialisation must be performed to convert the serial data stream to parallel. This is performed using additional logic in the control Field Programmable Gate Array (FPGA) of the HIFUARP system.

The design choice of converting the ADC output to serial, means that it is possible to feed the data back through a low-channel count digital isolator. This allows the exact same sense circuit to be used for both voltage and current measurement by simply floating the whole current sense and digitisation circuitry directly on the output of the pulser avoiding the need of any form of analog signal isolation. Digital isolators are available with bandwidth of up to 1Gbps with the necessary slew rate capabilities, which means that it is feasible to achieve fast sampling rates and high bit depths using floating converter circuitry.

In the case of the current experimental design, the current/voltage sense circuitry was a proof of concept, and available PCB space was heavily limited due to the boards being designed to fit in the existing UoL HIFUARP system. As a result the data rate of the converters was limited to 100 Mbps, equating to an 8-bit ADC running 12 MSps. A sampling rate of 11.43 MSps is used in the design to as it is the highest frequency integer division of the 80 MHz clocks used in the HIFUARP system that is within the restricted bandwidth. Even at this sample rate it is still possible to measure the 5th harmonic output of a standard 1.1 MHz fundamental transmit waveform, and the 3rd harmonic of a 1.7 MHz transmit waveform.

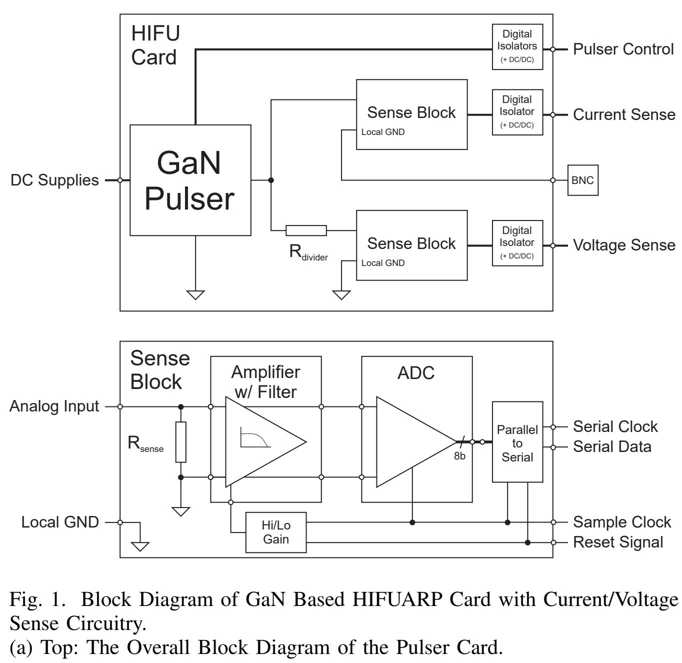


Fig. 1. Block Diagram of GaN Based HIFUARP Card with Current/Voltage Sense Circuitry.
(a) Top: The Overall Block Diagram of the Pulser Card.
(b) Bottom: The Block Diagram of the Sense Circuitry.

V. Experimental Results

The experimental GaN HIFUARP pulser card is shown in Fig. 2. To test the performance of the transmit waveform generation and current/voltage sense circuitry, the pusler card was installed in the UoL HIFUARP system and connected to two different loads, a 50 Ω resistive load, and a H-102 HIFU Transducer (Sonic Concepts) via matching network. A 20 μs 5-level HRPWM waveform was programmed into the HIFUARP system and the five voltage rails set for 0 V, ±50 V and ±100 V, giving a a 200 Vpp drive level.

Voltage and current measurements for the output of the pulser were captured using an MSO-S 204A Oscilloscope with N2873A Passive Voltage Probe and N2893A Active Current Probe (Keysight Technologies) to provide reference measurements. The voltage and current were simultaneously measured using the experimental I-V sense circuitry on the HIFUARP card. The results are shown for a 50 Ω load in Fig.3 and for the transducer load in Fig.4, both in the time domain and frequency domain.

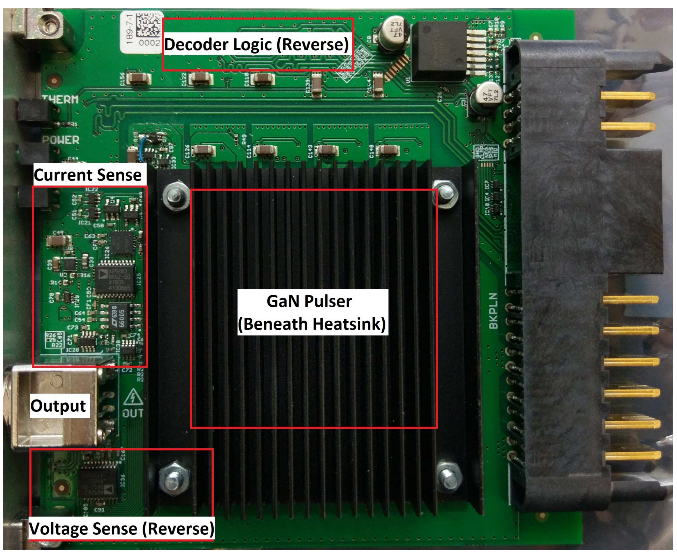
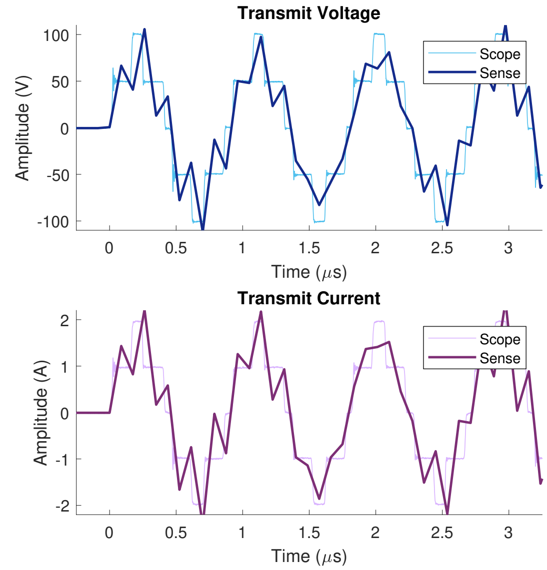


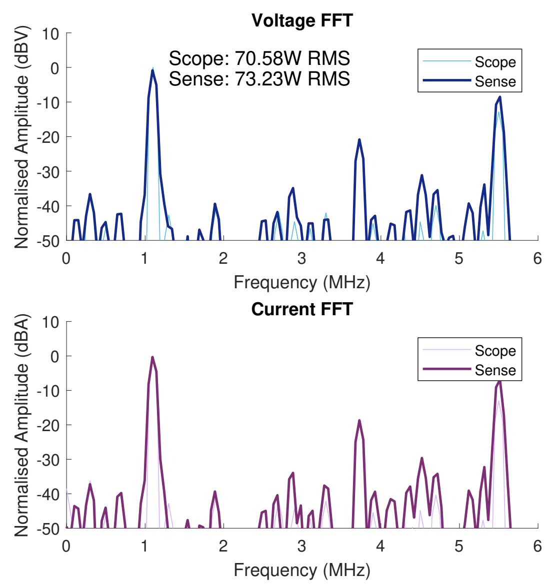
Fig. 2. Photograph of Experimental of GaN Based HIFUARP Card with Current/Voltage Sense Circuitry.

The time domain measurements for the sense circuitry shown in the figures must be understood to be heavily band-limited, being sampled at 11.43 MSps whereas the oscilloscope measurements are captured at 1 GSps. As such, comparison is best performed in the frequency domain. The frequency domain plots for both the oscilloscope measurements and the sense circuitry measurements show excellent correlation with each for the resistive load both in voltage and current. For the transducer load a good correlation is shown at the fundamental and fifth harmonics, though the current waveform shows signs of distortion which are likely due to distortion caused by clipping due to the initial portion of the waveform approaching the maximum input range of the amplifier stage.

In all results, a peak is visible at ∼3.8 MHz in the sense data but not in the oscilloscope data. This peak is caused



(a) Voltage and Current in Time Domain

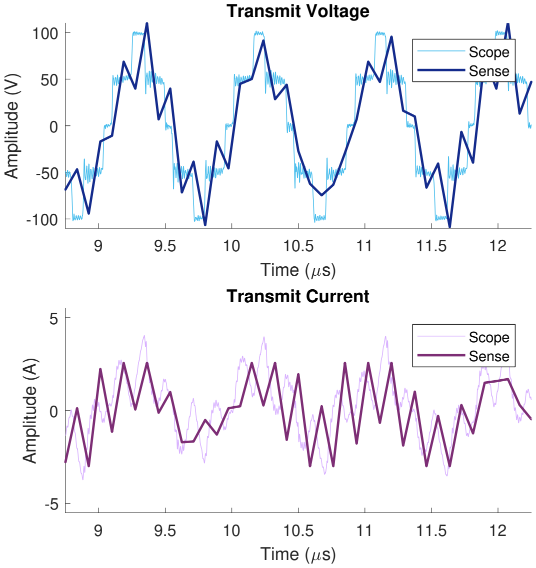


(b) Voltage and Current in Frequency Domain

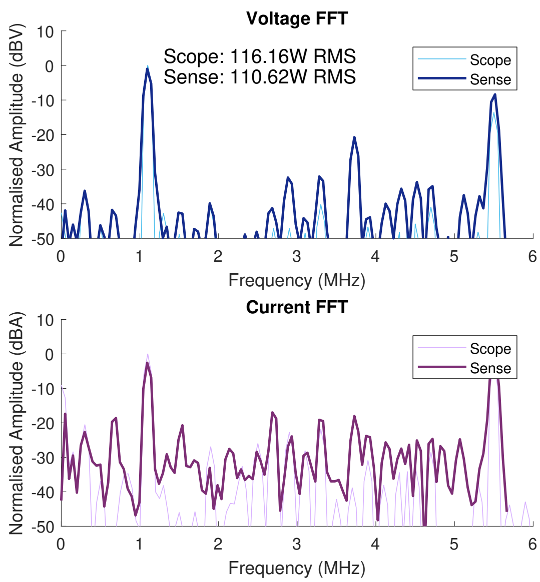
Fig. 3. HRPWM Output of GaN Pulser at 200 Vpp and 1.1 MHz into 50 Ω Load Measured By Keysight MSO-S 204A Oscilloscope an HIFUARP I-V Sense Circuitry. Estimated RMS Power is Indicated on Voltage FFT Plot

by aliasing of the seventh harmonic of the output waveform. While the experimental sense circuit does include an anti-aliasing filter, the roll-off of the filter is relatively slow, only provides approximately 10 dB reduction at 7.7MHz. This can be eliminated in future designs by adding an additional filter stage to increase the sharpness of the filter.

Of additional note is the output of the pulser circuit even into a complex transducer load provides a faithful recreation of the desired HRPWM waveform resulting in near total cancellation of the 3rd harmonic in the output waveform (-40dB below fundamental). Additional cancellation of the 5th harmonic is possible by changing HRPWM waveform.



(a) Voltage and Current in Time Domain



(b) Voltage and Current in Frequency Domain

Fig. 4. HRPWM Output of GaN Pulser at 200 Vpp and 1.1 MHz into Sonic Concepts H-102 Transducer Measured By Keysight MSO-S 204A Oscilloscope an HIFUARP I-V Sense Circuitry.

VI. Conclusions

This paper demonstrates an experimental switched-mode HIFU transmit pulser with built-in real-time current and voltage measurement, capable of delivering high powers at high frequencies whilst providing feedback on power delivered. The pulser has been demonstrated for driving a 1.1 MHz signal into both a 50 Ω load, and also a HIFU transducer. The sense circuitry uses a novel approach of floating the entire analogue front end on the output of the transmit pulser to allow simple high frequency high side current measurement.

For both load and transducer, the pulser is capable of faithfully replicating the desired HRPWM waveform allowing for excellent third harmonic reduction. Additionally the simultaneous current and voltage measurements show excellent correlation with reference oscilloscope waveforms showing that it should be possible to accurately provide real time power measurement.

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