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Development of a Hybrid Custom / Commercial Multi-Channel, High-Frequency Transmit Pulser and Beamformer System

Holly S Lay, Romans Poltarjonoks, Sandy Cochran
School of Engineering
University of Glasgow
Glasgow, UK
Holly.Lay@glasgow.ac.uk

David Lines
Diagnostic Sonar Ltd
Livingstone, UK

Florence N dum
School of Physics, Engineering and Mathematics
University of Dundee
Dundee, UK

Geoffrey R Lockwood (deceased)
Department of Physics, Engineering Physics and Astronomy
Queen's University
Kingston, Canada

Abstract—The progressive development of a custom series of microultrasound transmit circuits is presented, with bipolar operation in both single-pulse and extended pulse operation. We have developed a series of low-cost, expandable channel-count circuits to drive microultrasound transducer arrays at frequencies up to 50 MHz and voltages up to 80 V_{pp}. This includes both bench-top supply and electrical mains powered system development with expandable channel count and also includes integration with the multi-channel FI Toolbox commercial product (Diagnostic Sonar, Livingston, UK). A series of discrete focusing delay chips with variable delay steps allows them to be programmed either serially or in parallel. In turn, this allows the system to be operated in isolation or in conjunction with commercial generic hardware platforms.

Keywords— *Electronics, High-Frequency, Microultrasound, Pulser, Arrays, Multi-Channel*

I. INTRODUCTION

Microultrasound (μ US) array imaging above 25 MHz is a rich field of research, with applications in intravascular, endoscopic, ocular and dermatological imaging amongst many [1] – [4]. However, there has been some lag in the development of electronics required to drive and focus ultrasound arrays at these frequencies, with commercial solutions often suffering bandwidth, power or channel count restrictions.

Researchers working on prototyping μ US transducer arrays have, as a consequence, resorted to individual solutions combining commercial chip sets with custom circuit boards to achieve the required frequency and output voltage ranges. Simpler system architectures tend to use discrete delay stages [5], [6] to achieve beamforming delays, while more integrated designs use field programmable gate arrays (FPGAs) [7], [8] or application-specific integrated circuits (ASICs) [9], [10]. However, both the delay stage and FPGA-based designs use analog amplifier stages to achieve the final output voltages and ASIC-based designs are more suitable for low-power devices

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such as CMUTs because of the difficulty in achieving output voltages above 25 V [10]. All these solutions are primarily monolithic in nature, leading to difficulty in adapting them to alternative applications and in repairing individual channels.

To address the issue of adaptability and channel replacement, we have developed a modular transmit pulser design which has been adapted for use in pulse-echo and continuous-wave (CW) applications and in integration with a commercial system.

II. MICROULTRASOUND TRANSMIT PULSER DESIGN

A. System Requirements

Microultrasound transducer development in the range from 20 - 50 MHz often requires the development of custom electrical test equipment since, with only a few exceptions, commercial solutions are designed for operating frequencies below 15 MHz. The bandwidth requirement of μ US imaging is coupled with a need for high voltage on transmit, with more than 50V_{pp} drive desirable when working with ceramic piezoelectrics. Microultrasound transmitters (or pulsers) have the additional requirement to drive highly capacitive loads and the need to revert to a high-impedance output state when not driving the load to avoid damaging the receive circuits.

When working with array systems, transmit beamforming is also necessary to focus the resulting acoustic pressure wave. This requires the ability to specify a discrete delay on each pulser channel. This means that a transmit pulser / beamformer should have as many transmit channels as there are active array elements, and the ability to control the output timing of each of its channels independently.

To meet these requirements, we determined that our system should be capable of transmitting +50 V_{pp} pulses at up to 50 MHz with multiple channels with individual control and high-impedance output resistance when inactive.

B. Existing Systems

As mentioned previously, while research into the acoustic side of microultrasound imaging has seen significant advancement in the last few decades, commercial development of transmit circuits, in particular, has lagged. There are a few solutions available, however, each with its advantages and disadvantages.

As an example of a compact commercial transmit / receive solution, JSR provides the DPR500 (Imaginant Inc., Pittsford, USA), which is a dual channel pulser-receiver with a bandwidth of 300 MHz and a negative impulse mono-polar pulse drive. This unit is useful for testing of single-element transducers, but is of limited use in array testing applications due to its channel limitations.

A pair of single-channel chip solutions is available. One of these is the TX517 (Texas Instruments Inc., Dallas, USA) with a 50 MHz bandwidth and up to 200 V_{pp} output. However, this chip requires 10 separate voltage supplies, plus ground, and a separate digital drive source, making it a non-trivial exercise to power the chip. The other single-chip solution is the HV7360 (Microchip Technology Inc., Chandler, USA), with a 35 MHz bandwidth and up to 200 V_{pp} output. The lower bandwidth on this chip makes its functionality dependent on the frequencies of interest in a given application.

Based on the channel, bandwidth and power restrictions of the options available, the decision on which the work in this paper is based was to go with an amplification solution based on discrete devices, with beamforming delays supplied by delay chips.

III. SYSTEM DEVELOPMENT

The overall development of the custom system followed a series of stages from prototype benchtop system, suitable for use in an electronics lab, through a closed system optimized for use in continuous wave systems, to integration with a commercial beamforming system. The main amplifier components were maintained through all three systems, with small modifications to the circuit configuration, and additional components were determined by the functionality of each system. The core amplifier is a two-stage design using THS3001 (Texas Instruments, Dallas, USA) op-amps to boost a 2 - 5 V input signal to 12 V followed by a CMOS output stage comprising a ZXMP10A13F PMOS (M1) and a ZXMN10A07Z NMOS (M2) (Diodes Inc, Plano, USA) with a variable power supply to drive the output pulses (Fig. 1).

A. Analog Transmit Beamformer

During initial development of the pulser system, emphasis was placed on modularity and ease of programming of the beamforming delays. The use of an individual output board for each channel was adopted both for ease of maintenance and noise isolation. For this reason, a mother - daughter configuration was chosen, with main power and trigger signal being supplied to the motherboard and beamforming delays and output amplification being achieved on single-channel daughter cards. The daughter cards were designed in two

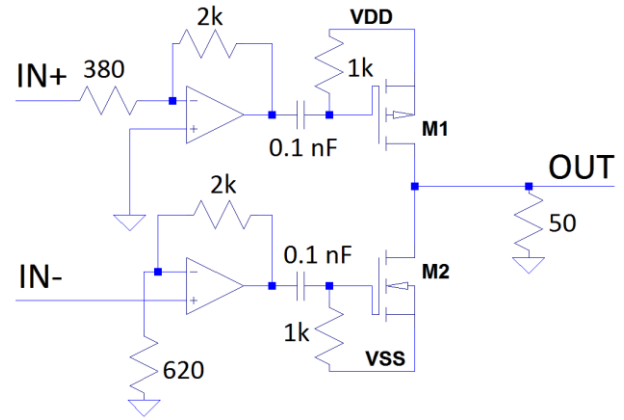


Figure 1. Core two-stage amplifier configuration used in the pulser systems

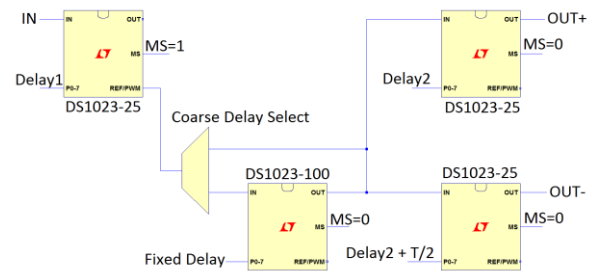


Figure 2. Transmit delay block from daughter card featuring analog delays

halves, one for pulse-shaping and delay-stages (Fig. 2) and the other for the core amplifier block.

The transmit beamformer block uses DS1023-25 and DS1023-100 pulse-width modulation (PWM) / delay chips (Maxim Integrated, San Jose, USA) to produce both frequency and delay control for each daughter card. The initial pulse shaping is achieved using a 1023-25 chip set to tracking mode. In this mode, the Ref output is a pulse the length of the programmed delay, corresponding to half the period of the final pulse, with the 0.25 ns step control on the DS1023-25 allowing very fine frequency control. This delay-length pulse is then output to the delay stages. In delay mode, the -25 chips delay the input pulse by up to 63.5 ns in 0.25 ns steps. To allow larger beamforming delays, a -100 chip was selectable via multiplexor which can add up to 255 ns of additional delay [11].

To program the pulse width and beamforming delays, each daughter card had a set of DIP switches on the back to directly program the parallel input to the DS1023 chips. To save board space, the coarse delay chip was hard-wired to a delay of 50 ns. These chips can also be programmed serially via SPI interface, an option used in the third system, for integration with a commercial beamformer.

B. CW Signals

While the modular system performed well in an electronic laboratory setting for pulse-echo work, the need for five power

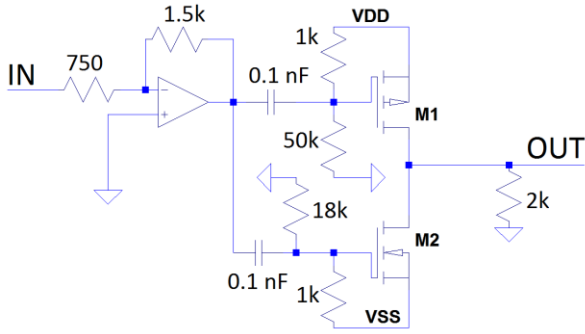


Figure 3. Modified two-stage amplifier for continuous wave output

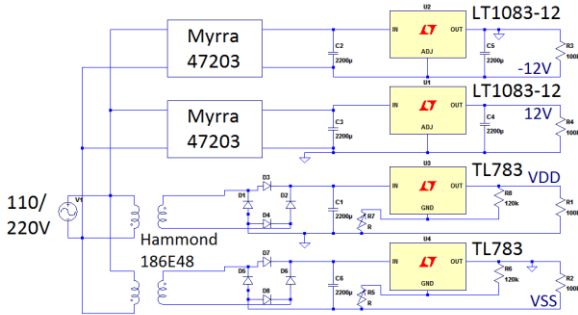


Figure 4. Power backplane for continuous wave transmit system

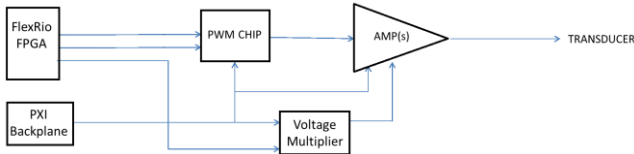


Figure 5. Adaptation of the analog transmit pulser circuit to work with the DSL FI Toolbox

supplies and the limitation to single pulse mode motivated further development.

To modify the system to work in CW mode, the beamforming component was removed, and the amplifier section modified in detail to reduce heat dissipation in the output MOSFETs (Fig. 3). In conjunction with this, a new power / trigger motherboard was designed and manufactured, with 220 / 110V_{ac} input and the required op-amp and MOSFET DC levels as output.

This also incorporated variable voltage control on the output stages, allowing continuous gain adjustment (Fig. 4). The entire system was encased in a custom enclosure fitted with both intake and exhaust fans to maintain air-flow and help temperature control.

C. FI Toolbox Integration

While the analog beamformer configuration was acceptable for bench-top tests, the analog delay control meant that the transmit delays could not be changed during real-time scanning. To adapt the analog transmit beamformer for use with continuously changing focal delays, there was a need for a

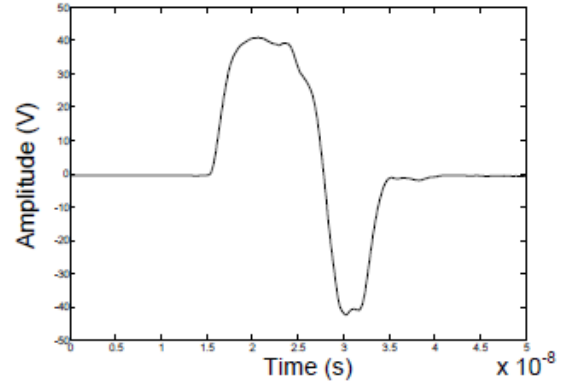


Figure 6. Output pulse from the analog transmit beamformer at 50 MHz and 90 V_{pp}

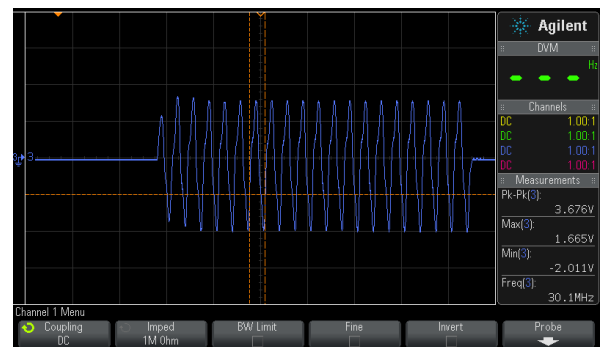


Figure 7. 20 cycle output pulse from continuous wave system at 30 MHz and 36 V_{pp}, obtained with 20 dB attenuation.

digital control system that could handle multiple channel control. Therefore, the researchers partnered with a company to adapt their FI Toolbox (Diagnostic Sonar Ltd., Livingston, UK) to work with this system. The FI Toolbox is a 32- to 1024-channel transmit / receive beamformer which has been characterized as having a transmit bandwidth of 24 MHz at 30 V_{pp} outputs [12]. As the existing system is configured to control the output module via a FlexRIO FPGA (National Instruments Inc., Austin, USA), the analog beamformer was adapted to receive delay control from the FPGA (Fig. 5).

IV. RESULTS

A. Analog Transmit Beamformer

The manufactured system had 12 daughter cards connected to the main power supply board which provided the necessary +5 V, ±12 V, V_{DD} and V_{SS} from bench-top supplies. V_{DD} and V_{SS} could be varied in the range 15 - 50 V, resulting in a maximum output pulse amplitude of 100 V_{pp}. The maximum output frequency was determined by the DS1023-25 pulse generator, which has rise and fall times of 2.5 ns, resulting in a maximum frequency of 50 MHz. The output waveform at 50 MHz and 90 V_{pp} is shown in Fig. 6.

B. Continuous Wave

The system was tested with four daughter cards and 20 cycle output pulses driven by linked function generators with variable delays. The system produced 60 V_{pp} pulses at 30 MHz and 25 V_{pp} at 50 MHz and was thermally stable with built-in air cooling at 30 MHz with 50% duty cycle (20 cycles on, 20 cycles off) (fig. 7).

C. FI Toolbox Integration

Initial prototypes failed to implement the necessary voltage tripler power system; however, stand-alone testing using lab-built boards successfully output 50 MHz pulses at 16 V_{pp} and 25 MHz pulses at 37 V_{pp}. Loss of bandwidth compared to the analog system was attributed to non-ideal grounding conditions on the circuit boards and comparison of similar circuits has shown bandwidth improvement with correct grounding design.

V. DISCUSSION AND FUTURE WORK

Over the course of development of the three related systems presented in this paper, the strengths and suitability of each approach to particular applications has become apparent. The analog transmit beamformer system has the advantage of simplicity, both in manufacturing and application, and it achieves very clean output pulses. However, the analog delay control and the need for bench-top power supplies makes it best for use in environments where the focus delays do not need constant adjustment. It is also prone to excess heating of the load resistor when driving high-impedance transducers.

The CW system addresses the heating and power supply issues of the first system, allowing a single box solution which still retains the modularity of the original design. As a trade-off, the beamforming delays must now be supplied by an external source and some loss of bandwidth was seen as necessary to avoid overheating.

The system integrated with the FI Toolbox allowed the simple functionality of the analog system to be combined with digital control of the beamforming delays and central power systems. This eliminated the drawbacks of the first system, with the only reduction of functionality being the loss of modularity of the channels. The FI Toolbox system still incorporates a lower level of modularity, as well as including a full receive system as well, making the trade-off more than acceptable.

The existing systems show excellent functionality for their current applications, as well as ease of adaptability to new applications as they arise. As a group, they cover a range of

user specifications in a way which makes them a robust solution to μ US array testing, whatever the application.

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