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Synchronized and configurable source of electrical pulses for x-ray pump-probe experiments

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A method is described for the generation of software tunable patterns of nanosecond electrical pulses. The bipolar, high repetition rate (up to 250 MHz), fast rise time (<30 ps), square pulses are suitable for applications such as the excitation sequence in dynamic pump-probe experiments. Synchronization with the time structure of a synchrotron facility is possible as well as fine control of the relative delay in steps of 10 ps. The pulse generator described here is used to excite magnetic nanostructures with current pulses. Having an excitation system which can match the high repetition rate of a synchrotron allows for utilization of the full x-ray flux and is needed in experiments which require a large photon flux. The fast rise times allow for picosecond time resolution in pump-probe experiments. All pulse pattern parameters are configurable by software.

I. INTRODUCTION

Pump-probe-type experiments are frequently utilized to study subnanosecond phenomena in physical, chemical, and biological systems.[1–10] In such studies an excitation ("pump") is applied to the system of interest and, after an adjustable time delay, a measurement ("probe") is performed. The pump is frequently an electrical, magnetic, or optical excitation, while the probe is often an ultrafast absorption, scattering, or resistance measurement which can be performed with a laser, x-ray source, or fast electronics. The probe signal as a function of time delay then yields information on the dynamics induced by the excitation. Typically, many such pump-probe cycles must be averaged in order to acquire sufficient signal-to-noise ratio in the measurement. In this article, we describe instrumentation for the generation of electrical pulses for use in pump-probe experiments. The electronics was especially designed to meet the unique challenges involved in the use of a synchrotron x-ray source as a probe.[2,4–8] Synchronization with such a source requires the flexibility to accommodate the various operating modes of the synchrotron. For this reason, software configurability of the excitation pulse pattern was designed into our instrumentation. An example of an efficient detection system specifically for x-ray absorption measurements is described in Ref. 11. However, synchronizing the electrical pulses with other detection schemes, such as a laser or electrical probing system, is easily accommodated.

II. PULSE PATTERN SYNCHRONIZATION

In order to perform time-resolved studies, synchronization with the synchrotron x-ray source is required. Electrons in a synchrotron make a regular orbit around the storage ring, typically within 1 μs. Within this orbit electron bunches can be filled in regularly spaced ($\sim$2 ns) "buckets." The electron bunches generate x-ray pulses. The specific filling pattern can vary significantly for different modes of operation. Thus, the challenge for a pump-probe experiment is not only to exactly synchronize to these bunches with a well-defined phase but also to have a "filling" pattern of pulses which matches the filling pattern of the storage ring. One way to accomplish this is to conduct experiments in a low filling mode of the synchrotron or to gate x-ray bunches without a corresponding electrical pulse.[12,13] However, a design is desired which allows efficient use of all x-ray bunches and which can accommodate many modes of operation. Note that this ability to match arbitrary synchrotron patterns adds significant flexibility to the pulse generator and allows one to use detection schemes other than x rays.

III. INSTRUMENTATION

The instrumentation described here provides a way to generate software-defined pulse patterns that can be synchronized and matched exactly to the bunch structure of a synchrotron. The primary features of the system described here are (1) fast rise times of <30 ps and low jitter in the excitation pulse in order to achieve the best time resolution, (2) precise synchronization of the excitations with various detection schemes, (3) high repetition rate up to 250 MHz, and (4) pulse configurability (amplitude, pattern shape, delay, etc.) in order to accommodate the relaxation time of the sample or the time structure of the probe system.

Figure 1 gives an overview of the system. To increase flexibility we use a field programmable gate array (FPGA)

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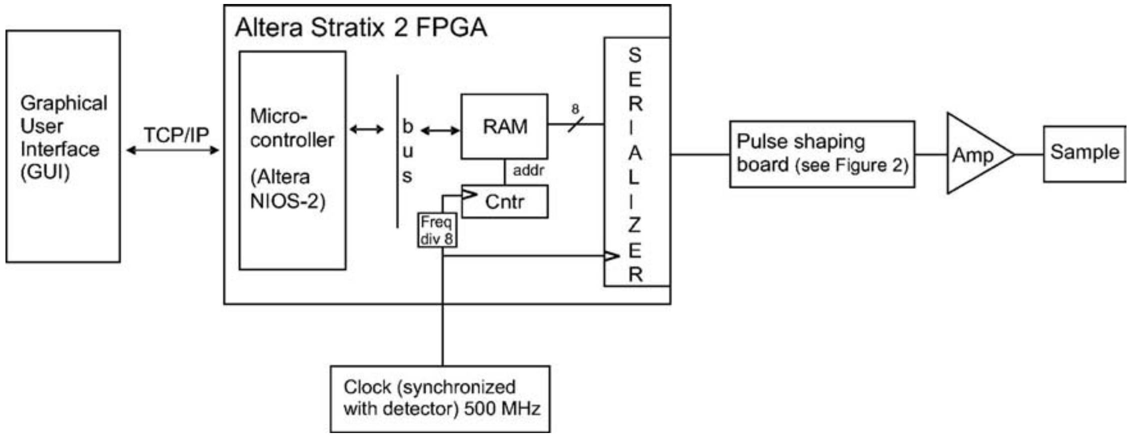

FIG. 1. Overview of the pulse pattern generator. A graphical user interface is used for easy configuration of the pulse pattern via TCP/IP. The FPGA implements the generation of the pulse pattern which is stored in a RAM as 8 bit words. A counter running at $\frac{1}{8}$ of the 500 MHz bunch rate of the synchrotron source is used to address the RAM. As this counter is reset by the orbit frequency of the synchrotron, each bit in the RAM is associated with a specific bucket number of the synchrotron source. The 8 bit data output of the RAM is serialized to generate a bit stream indicating on which bucket a pulse is generated. The output of the serializer is used to trigger the pulse shaping board where a well defined pulse is formed. Additional amplification provides the amplitude required for the experiment.

for pulse pattern generation and synchronization to the synchrotron and special hardware to implement the finer time control ($\sim$10 ps). TCP/IP is used to communicate from a graphical user interface (GUI) front end to the pulse configuration system on the FPGA. The particular x-ray photon counting system used in our experiment is described elsewhere,[11] but it is worth noting that clock signals are shared between the excitation and detection hardware, and the relative phase delay is then adjusted in the excitation hardware to put the two systems in synchronization. The FPGA used is an Altera Stratix-2 which can implement a resident soft core processor. This processor runs a real time operating system (eCOS) which is used to communicate with the GUI through TCP/IP and gives access to the random access memory (RAM) banks for generating patterns.

An arbitrary pulse pattern is simply a sequence of 1's and 0's designating pulser on and off, respectively, generated at the bucket frequency (in our case 500 MHz). This pulse pattern is represented in the RAM of the FPGA as a sequence of 8 bit words. For generating the pulses, the RAM is ad-

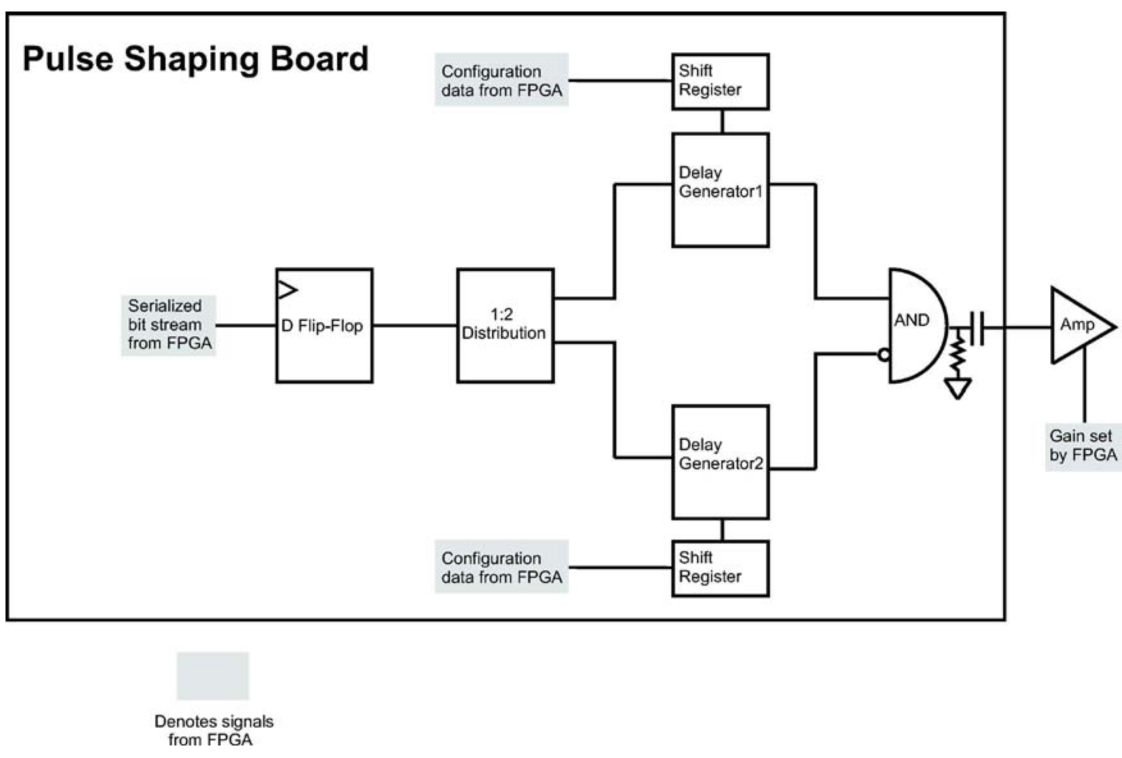

FIG. 2. (Color online) Schematic of pulse generating hardware. Signals from FPGA are shown in gray. The bit stream from the FPGA is resampled by a D-Flipflop to the 500 MHz bunch frequency to improve the timing jitter. After that, the signal is delayed by two delay generators. Delay generator 1 defines the start time of the pulse, whereas delay generator 2 determines its end time. All parts except for the amplifier and shift registers are from the high speed emitter coupled logic (ECL) family. Also note that all high speed signals shown are differential.

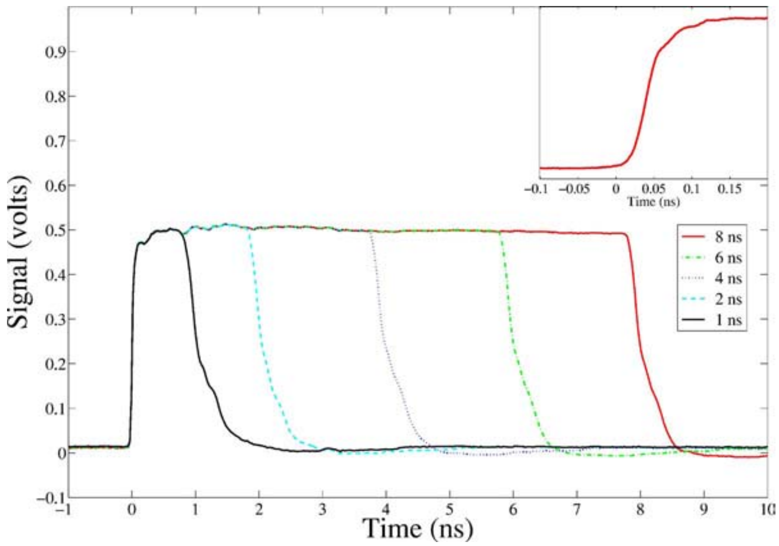

FIG. 3. (Color online) Resulting wave form output from the pulse generator for pulses of width 1, 2, 4, 6, and 8 ns. Inset shows the rising edge of the pulse.

dressed by a counter which is incremented at the bunch frequency of 500 MHz divided by 8 and reset at the orbit frequency of the synchrotron. Therefore, each bit of the RAM corresponds to a particular bucket of the storage ring. The data output from the RAM is serialized into a bit stream. The pulse shaping circuit described below transforms this bit stream into pulses of the proper width, start delay, and amplitude. Figure 2 shows a schematic detailing the pulse shaping circuit. In order to meet our strict timing requirements, this hardware has been developed using high performance silicon germanium devices made by ON Semiconductor as part of their GigaComm part family.

Generating pulses from the bit stream works in the following way: the bit stream from the FPGA is resampled by a fast D-Flipflop (ON Semiconductor, NBSG53A) clocked by the bucket clock in order to reduce timing jitter and distributed along two different paths (clock distribution chip—ON Semiconductor, NBSG11). The top path is delayed (delay generator 1, ON Semiconductor, MC100EP195) to set the desired start time of the pulse and the bottom path is delayed (delay generator 2) to set the stop time. By inverting the bottom wave form and performing a logical AND (ON Semiconductor, NBSG86A) with the top signal, a pulse of the desired width and timing is generated. The resulting signal is then ac coupled and amplified by a bipolar amplifier (Picosecond Pulse Labs, model 5865). Nonlinearities of the amplifier lead to steepening of the pulses. The gain of the amplifier is tuneable with an output voltage of maximum 4 V.

IV. RESULTS AND BIPOLAR PULSES

Figure 3 shows resulting wave forms delivered from the pulse generating hardware for various controllable pulse widths. Pulse width and start delay are adjustable in 10 ps steps, allowing very fine control for time-resolved studies. The wave form at the output of the amplifier has a rise time of ~100 ps. Since this will ultimately set the limit in the time resolution for a pump-probe study, it is desirable to improve this rise time. This can be done with a nonlinear transmission line (e.g., Picosecond Pulse Labs, Part 7003) which introduces a voltage-dependent group delay. These devices perform best when operated with a forward bias current (5–10 mA). A rise time of ~30 ps was attained, as shown in the inset in Fig. 3. The rise time is defined as the transition

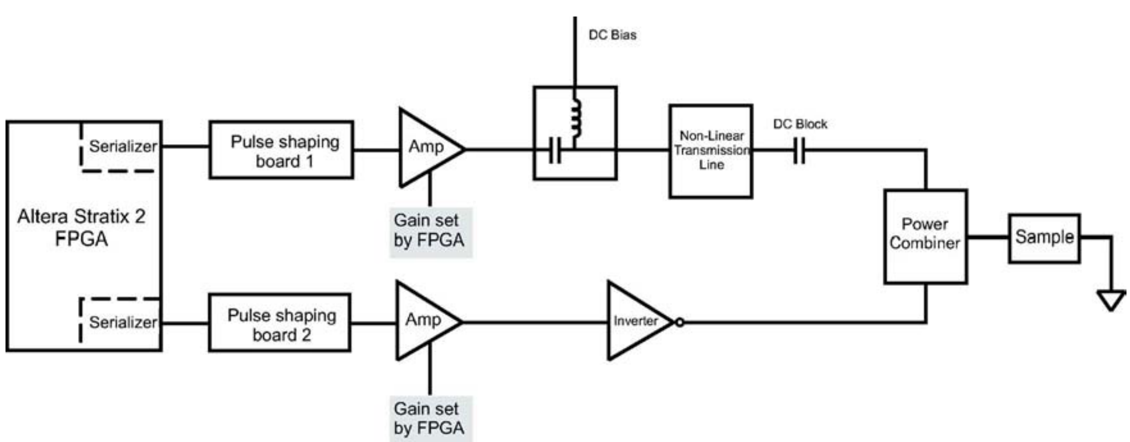

FIG. 4. (Color online) Schematic showing configuration for generating bipolar pulse patterns. Two pulse shaping boards are used. Along one path (bottom), the pulse is inverted. Along the other path (top) the pulse is compressed through a nonlinear transmission line. Pulses are combined in a resistive rf power splitter.

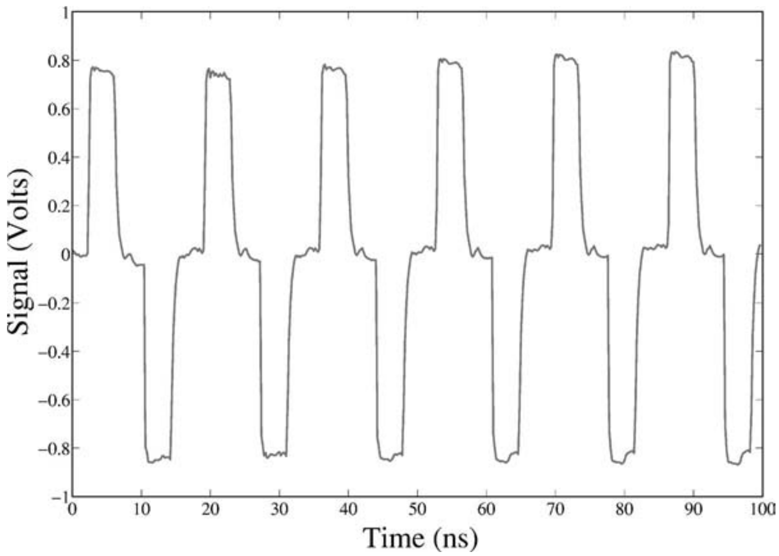

FIG. 5. Pattern of positive and negative pulses at 62.5 MHz.

time between 20% and 80%. We have also found that cascading two nonlinear transmission lines can reduce the rise time to 20 ps.

Figure 4 shows how to generate a high repetition rate pulse train of positive and negative pulses (as used for the experiment in Ref. 7). This bipolar pattern was generated by using two pulse shaping boards as well as amplifiers, inverting the output of one, and combining the outputs in a resistive power splitter. In the experiment, the positive pulse was used to excite the magnetization reversal of a nanopatterned device, and the negative pulse was used to reset the magnetic state. Hence, it is only the positive pulse rise time which sets the time resolution for the dynamics of interest and a nonlinear transmission line was used on the positive pulse only. Resulting wave forms are shown in Fig. 5.

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