Many physical systems can be used as a qubit. Their viability, however, relies on how carefully their state can be controlled. In a number of schemes (such as ionic and NMR qubits), this control is provided by carefully sculpted waveforms. By improving the precision of these waves, the fidelity of the qubit is improved. We are building a pulse programmer to meet the need for precisely constructed waveforms in quantum computing. It synthesizes waves, allowing users to carefully design arbitrary waveforms.

Pulse Programmer:

Overview
The pulse programmer addresses several needs in one device. It will offer greater control over our lasers, for more reliable measurement of the qubit state. Once integrated into experiment, it will serve as a command hub to synchronize all of our lab equipment to one clock, and will serve to automate some processes by responding to events in the lab.

Summary of Operations
A pulse program is written in python with high level functions that generate FPGA commands. These programs specify arbitrary waveforms in amplitude, frequency, and initial phase offset, the timing of digital outputs, and logical responses to digital inputs. This program is loaded into the FPGA, where it runs without further communication with the computer.

Breakout Board (A): The breakout board distributes signals from the FPGA to the digital outputs and DDS bus (B), and returns digital inputs to the FPGA. At startup, it also sends an initialization script to the internal clock and clock divider boards.

Direct Digital Synthesis (DDS) Boards (C): The DDS boards synthesize arbitrary waveforms by updating the frequency and amplitude of the waves it generates many times during a single pulse (up to once every 40ms). These properties are updated on the DDS board, but controlled by the FPGA via a data bus that addresses individual DDS boards. This will allow for more reliable adiabatic transfer of electron state. Additionally, the phase of these waves relative to the pulse programmer's clock cycles may be offset every 10 ns. This feature is particularly useful for qubits.

Clock: An internal 1 GHz clock is divided to 100 MHz as the clock source for both the programmer and clock divider boards. This feature is particularly useful for qubits.

Barium as a Hyperfine Qubit:

$^{137}$Ba is a strong candidate for use as a qubit because the energy states of its valence electron are well suited to meeting the needs of a qubit.

Coherence: The qubit formed by the hyperfine levels of $^{137}$Ba 6S ground state has a very long coherence time. For example, its decay due to spontaneous emission is negligible on the time scale of our civilization. One of the limiting factors for coherence is currently the magnetic field noise, mainly due to the 60Hz line noise.

Isolation: We trap $^{137}$Ba in a Linear Paul trap and cool it via laser cooling. For cooling, we bombard the ion with a few microWatts of 493nm laser light with 8GHz sidebands to drive transitions to the 6P ground state from either hyperfine sublevel of the ground state. The 6P ground state has a natural lifetime of about 8ns, allowing recooling of the ion between qubit manipulations over the course of 20 milliseconds. A separate 650 nm laser is used to repump the ion from the metastable 5D state.

State Manipulation: The 6S, 6P, and 5D states, involved in cooling, allow the qubit state to be initialized to zero via optical pumping. Once initialized, the state may be rotated to any superposition of ‘0’ and ‘1’ state by inducing Rabi flips between the two states with 8GHz microwaves. Rabi flips are a reliable means of rotating the qubit state because of the stability and precision of the synthesizers used for these operations.

State Measurement: $^{137}$Ba has a long lived (~30s) 5D$_{3/2}$ state that is well suited to qubit state detection when used in conjunction with the cooling lasers in a two-step measurement scheme. First, the 0’’ → 5D$_{3/2}$ transition is stimulated with a stabilized fiber laser at 1762 nm, placing the electron in the long lived state if it was originally in the ‘0’ state. Then, the cooling lasers are turned on. If the electron had been in the ‘0’ state, it will not be available for the cooling cycle, and the ion emits no photons (it appears dark). If, however, the electron had been in the ‘1’ state, then it is not banished to the 5D$_{3/2}$ state, and cycles with the cooling lasers, emitting 10 photons per second which are easily detected by a CCD camera (it appears bright see figure above).

The accuracy of this measurement scheme hinges upon the reliability of targeting the ‘0’ → 5D$_{3/2}$ transition 100% of the time, and never stimulating the ‘1’ → 5D$_{3/2}$ transition. This is a difficult task with Rabi flips because the 1762 nm laser frequency can drift by 10s of kHz over short periods of time, and the reliability of Rabi flips are heavily frequency dependent. This transition is more reliably made by adiabatic passage, so we seek better control over laser amplitudes and frequency sweeps.

Future Work:
API for Generating Waveforms: We are writing a set of functions to the python API for designing arbitrary waveforms. These enable users to write and edit waveforms quickly and avoid the low-level FPGA commands in their design.

Input Counting: We are writing firmware for the FPGA to count inputs and store this value in memory. This will allow the pulse programmer to take data, and is necessary to running programs that respond to more advanced signals than triggering on digital inputs.

Branching Based on Memory: We will add a set of branch-on-condition functions to the sequencer API that allow programs to respond to the current memory state. This will allow the pulse programmer to respond to complex lab events (such as determining the qubit state by counting photons received by the CCD camera).

Enable Parameter Scanning: We are writing FPGA firmware to increment the frequency value sent to the DDS boards. At present, waveforms are synthesized by reading an array of values for frequency and amplitude. This will remove this inefficient use of memory during frequency sweeps.

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