The qubit states can be manipulated with microwave pulses, whose frequency $\nu$ is proportional to the energy $E = hf$ of the qubit system.

A π-rotation is typically obtained using a 50ns Gaussian pulse for transmons. This is achieved by utilizing current-bleeding in the DAC to provide high linearity. A 10-bit segmented (5T-5B) current-steering DAC is used.

Quantum computers (QC), comprising qubits and a classical controller, can provide exponential speed-up in solving certain problems. Among solid-state qubits, transmons and spin-qubits are the most promising, operating << 1K. A qubit can be implemented in a physical system with two distinct energy levels (Fig. 19.1.1). For transmons, $E = hf$ is used, allowing the use of a single external LO.

The DDS is clocked at 1GHz with 32 numerically controlled oscillators (NCO) with 0.2kHz frequency resolution and 25MHz noise bandwidth. To control both spin qubits and transmons, we designed a controller with unaddressed qubits [4]. This demands a linear transmitter architecture with good phase offset to efficiently re-use envelopes for different rotation axes. The use of injection-locked oscillators is required to generate the required data rate to the controller, which is further reduced to ~1kb/s by the integrated programmable instruction set executed on external trigger with minimal delay between instructions. The versatility of this design is demonstrated in Fig. 19.1.4 showing the measurement of an instruction sequence containing 5 unique waveforms targeting 5 different qubit frequencies.

To compare with the state-of-the-art qubit controller ICs [1], this work exhibits a wide frequency and output power range compatible with multiple qubit technologies. The frequency multiplexing architecture potentially enables multi-qubit control over a single RF-cable, leading to a scalable system. The digitally-intensive architecture enables waveform shaping flexibility, minimum execution latency and straightforward integration in the existing quantum computing stack.

Acknowledgements:

References:
Figure 19.1.1: Qubit control signals, current state-of-the-art controller and presented cryogenic controller with frequency multiplexing.

Figure 19.1.2: Block diagram and transistor level schematic (bias circuitry not shown).

Figure 19.1.3: Measured RF Bandwidth, BB-Out transfer function, RF-Low output with NCO frequency at 350MHz, two-tone RF-Low output with NCO frequencies at 241MHz and 260MHz, all at 3K.

Figure 19.1.4: Qubit pulse shaping; top-to-bottom: digital backend, measured BB-Out signal and RF-Low spectrum (LO at 6GHz), both at 3K.

Figure 19.1.5: Rabi oscillation and coherent qubit control experiments at 14GHz and 18GHz with the controller IC at 3K.

Figure 19.1.6: Comparison table.
Figure 19.1.7: Die micrograph (without metal layers) with cut-out of a single transmitter showing I/O bumps and RF transformers, chip package and PCB with enclosure.

Figure 19.1.S1: Top to bottom, left to right: dilution refrigerator, qubit sample SEM, PCB enclosure (open & closed), chip and qubit mounting in the fridge and measurement setup block diagram.

Figure 19.1.S2: Measurement of on-chip and refrigerator temperature (chip on X4K-plate) vs power by sweeping digital supply and clock frequency, full RF-Low two-tone spectrum at 3K and DAC INL measurement explaining HD2.

Figure 19.1.S3: RF-High output with NCO at 350MHz. Two-tone RF-High output with NCOs at 241MHz and 260MHz. Noise spectral density and power consumption of various circuit blocks, all at 3K.