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Circuit QED Pulse Control Interface

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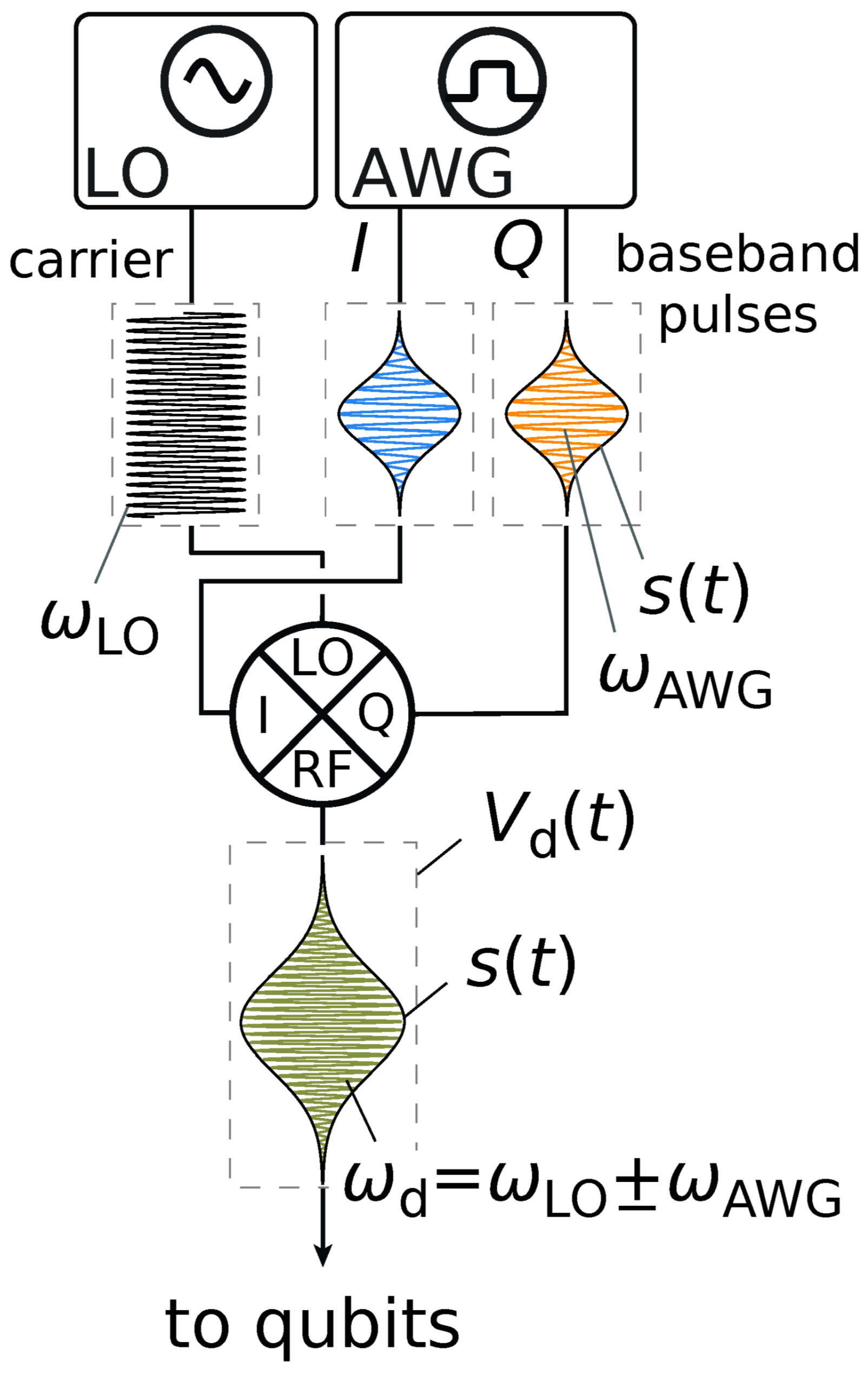
Introduction

Circuit Quantum Electrodynamics (circuit QED) leverages strong coupling between microwave photons and superconducting qubits for precise quantum state control via engineered pulses. Our Pulse Control Interface streamlines the design and testing of circuit QED control signals through a graphical user interface (GUI), incorporating two key protocols for state manipulation:

- SNAP-Displacement Protocol: Combines Selective Number-dependent Arbitrary Phase (SNAP) gates and displacement operators to modulate the states within a cavity. The SNAP gate applies a phase θ_n to each photon number state $|n\rangle$: $S(\vec{\theta}) = \prod_{n=0}^{\infty} e^{i\theta_n |n\rangle\langle n|}$. Displacement operators shift the state in phase space: $D(\alpha) = e^{\alpha a^\dagger - \alpha^* a}$, where α is the amplitude, $a^\dagger|n\rangle = \sqrt{n+1}|n+1\rangle$, and $a|n\rangle = \sqrt{n}|n-1\rangle$.
- ECD Protocol: Uses a qubit-state-dependent control mechanism. The Echoed Conditional Displacement (ECD) gate, expressed as $ECD(\beta) = D\left(\frac{\beta}{2}\right)|e\rangle\langle g| + D\left(-\frac{\beta}{2}\right)|g\rangle\langle e|$, employs β, a displacement parameter, and echoes via a qubit π-pulse. The protocol also involves qubit rotations: $R_\phi(\theta) = e^{-i\theta\,(\cos\phi\,\sigma_x + \sin\phi\,\sigma_y)}$, to adjust the phase.



Schematic of qubit drive setup in circuit QED. Baseband pulses from an arbitrary waveform generator (AWG) are combined with a carrier signal using an IQ mixer to create specific qubit control waveforms.

Additionally, users may import custom signals from CSV files, which allows for the integration of diverse control protocols. Signals can also be saved to CSV and later loaded as custom operations or applied in experiments. The CSV format and utility functions are customizable to align with specific firmware or processing requirements.

Conclusion & Future Directions

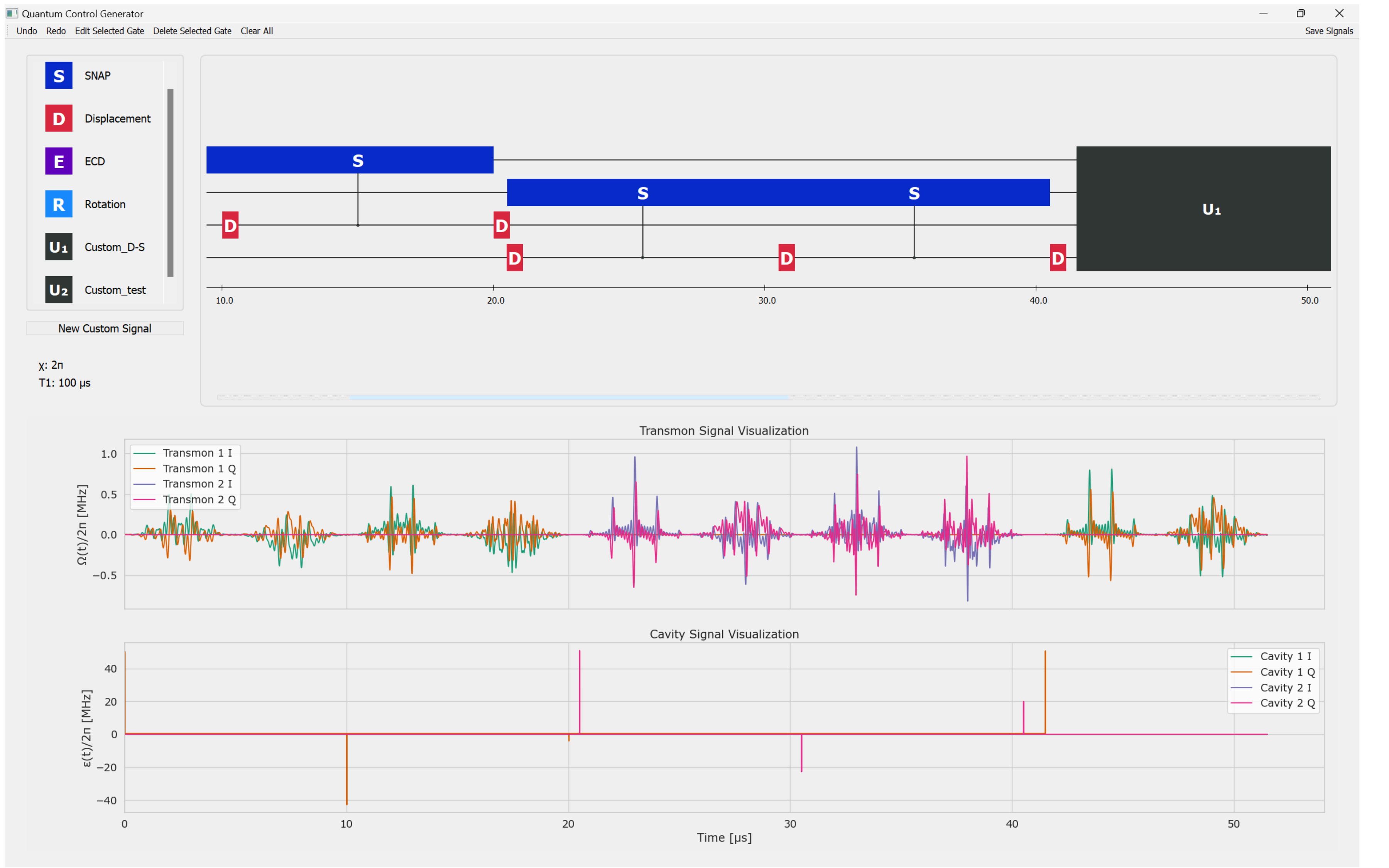
We have successfully developed a tool for efficient circuit QED control implementation, demonstrating high fidelity in quantum state preparation. Future efforts will focus on interfacing the application with circuit QED hardware and enhancing overall system performance. Plans include improving existing protocols by integrating noise models and error correction techniques and addressing sampling rate precision issues.

The software for this project is open-source and available for further development and review on GitHub: https://github.com/yuqing-lin/quantum-control-generator.git

SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

References

1. Blais et al., Rev. Mod. Phys., 93, 025005 (2021).
2. Heeres et al., Phys. Rev. Lett., 115, 137002 (2015).
3. Eickbusch et al., Nature Phys., 18, 1464-1469 (2022).
4. Krantz et al., Appl. Phys. Rev., 6, (2019).

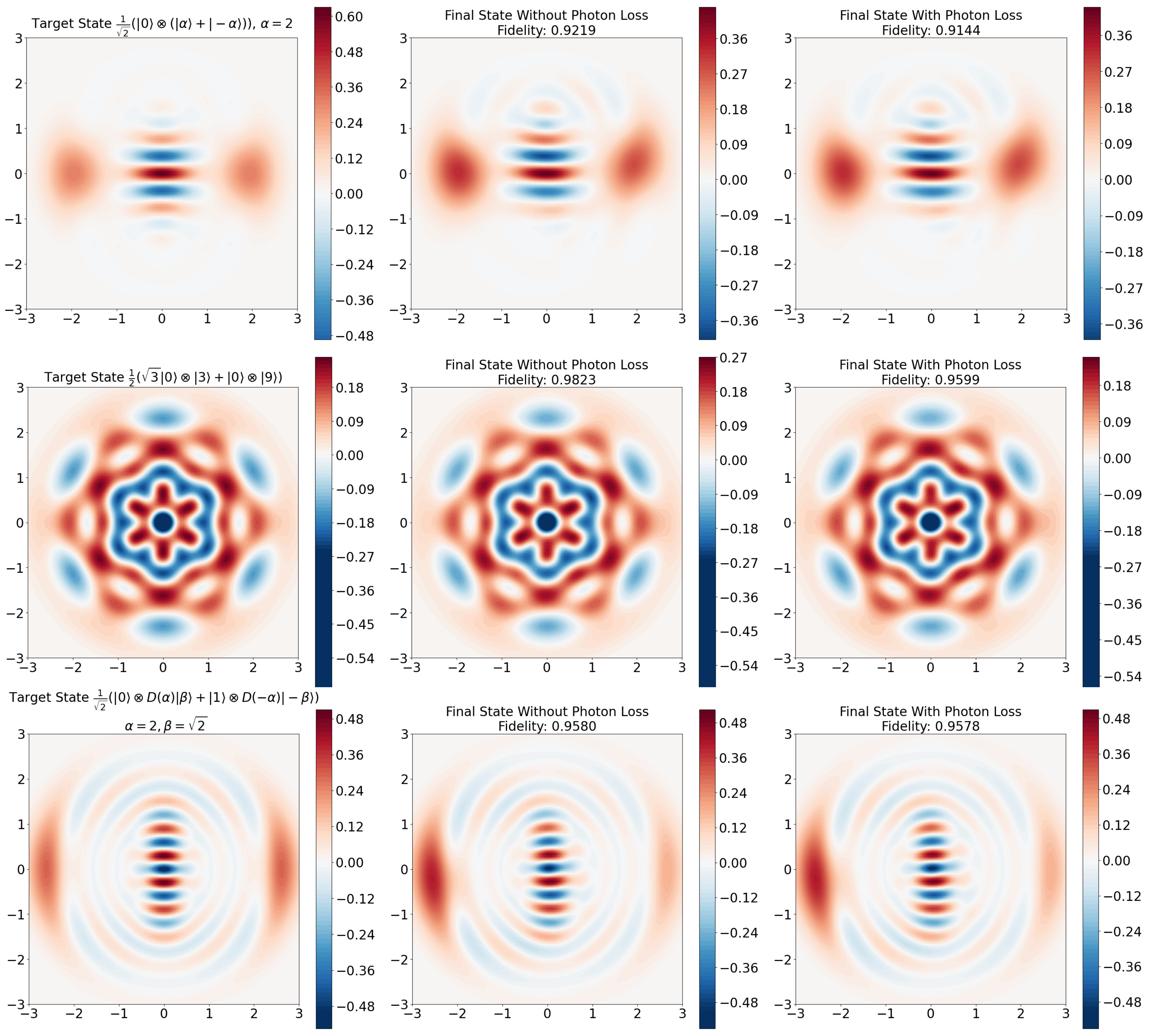


χ: 2π
T1: 100 μs

Screenshot of the GUI: Visualizes the assembled quantum circuit with corresponding pulse parameters and real-time signal waveforms for transmon and cavity control.

Methods

The interface features a drag-and-drop PyQt5 GUI for assembling quantum circuits. The signal generation module creates pulse envelopes based on user-defined parameters such as amplitude, phase, waveform, and duration. Real-time visualization of the control signals generated provides instant graphical feedback.



Wigner function QuTiP simulation results for quantum states prepared using the SNAP-Displacement protocol (D-S-D-S-D) in a system with 1 transmon and 1 cavity (2+10 levels). Simulations include drift Hamiltonian $H_d = -\chi a^\dagger a c^\dagger c$ and control Hamiltonian $H_c = f(t)\left(a^\dagger + a\right) + g(t)\left(a^\dagger - a\right) + h(t)\left(c^\dagger + c\right) + j(t)(c^\dagger - c)$, where $f(t)$, $g(t)$, $h(t)$, $j(t)$ are of the form $A(t)e^{i(\omega t+\phi)}$, and $a^\dagger$, a, $c^\dagger$, c are the creation and annihilation operators for the transmon and cavity. Each row displays the target state, the final state without photon loss, and the final state with photon loss, assuming a qubit lifetime of $T_1 = 100\ \mu s$.

QuTiP simulations were utilized to verify the fidelity of state preparation using the implemented protocols. The fidelity values confirm that the states closely match the theoretical predictions.

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