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Ultracoherent SRF cavity-based multi-qudit platform with error-resilient control

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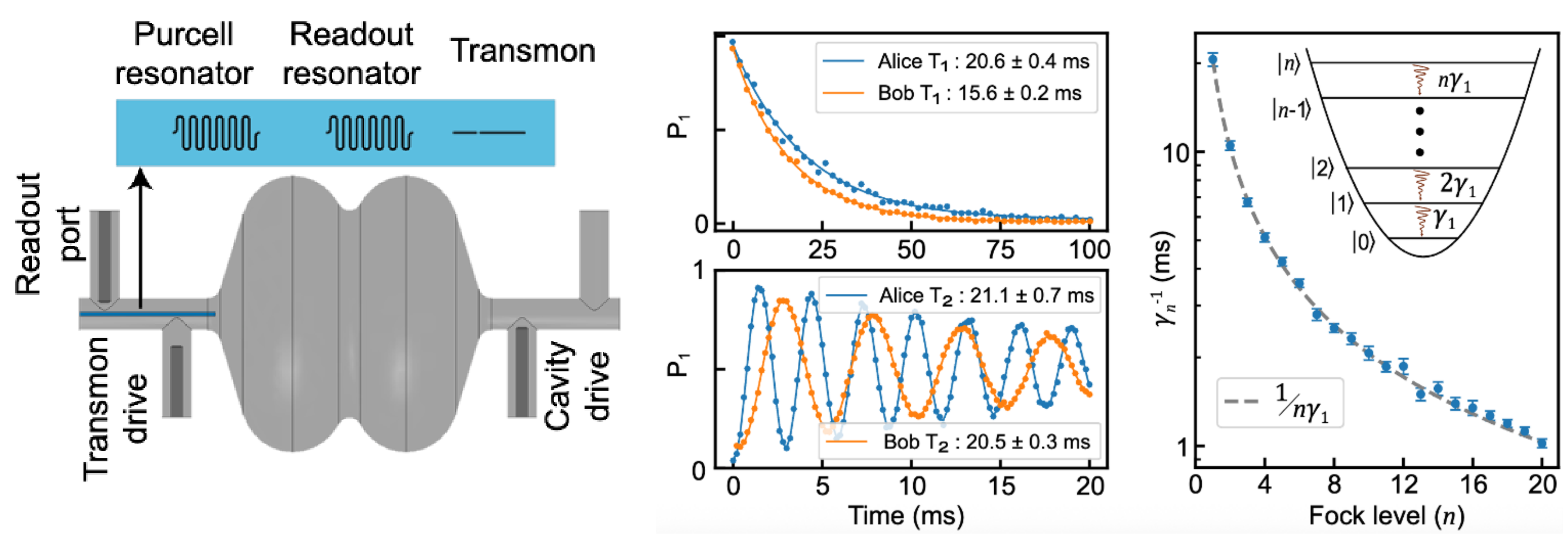
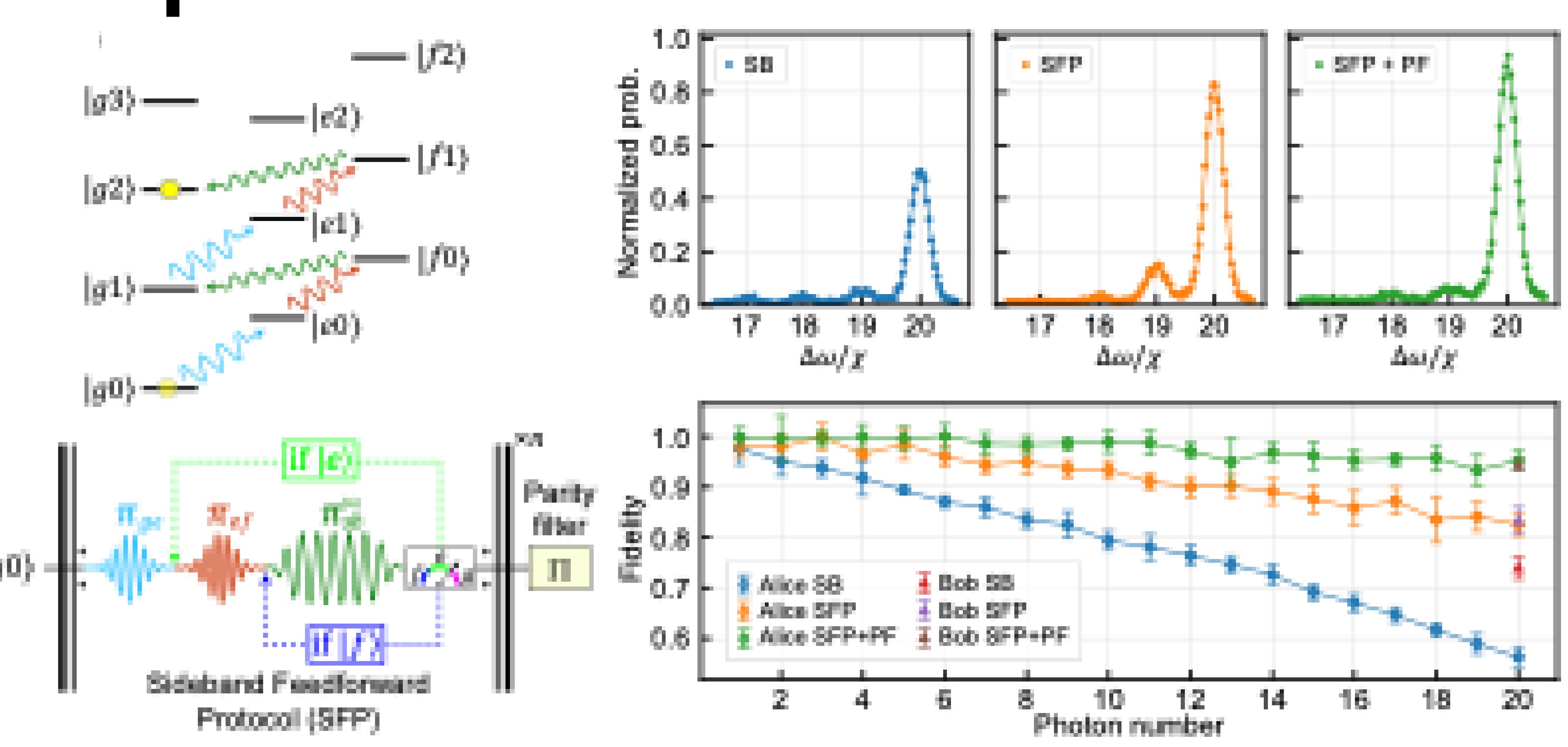
Ultracoherent Two-mode Cavity



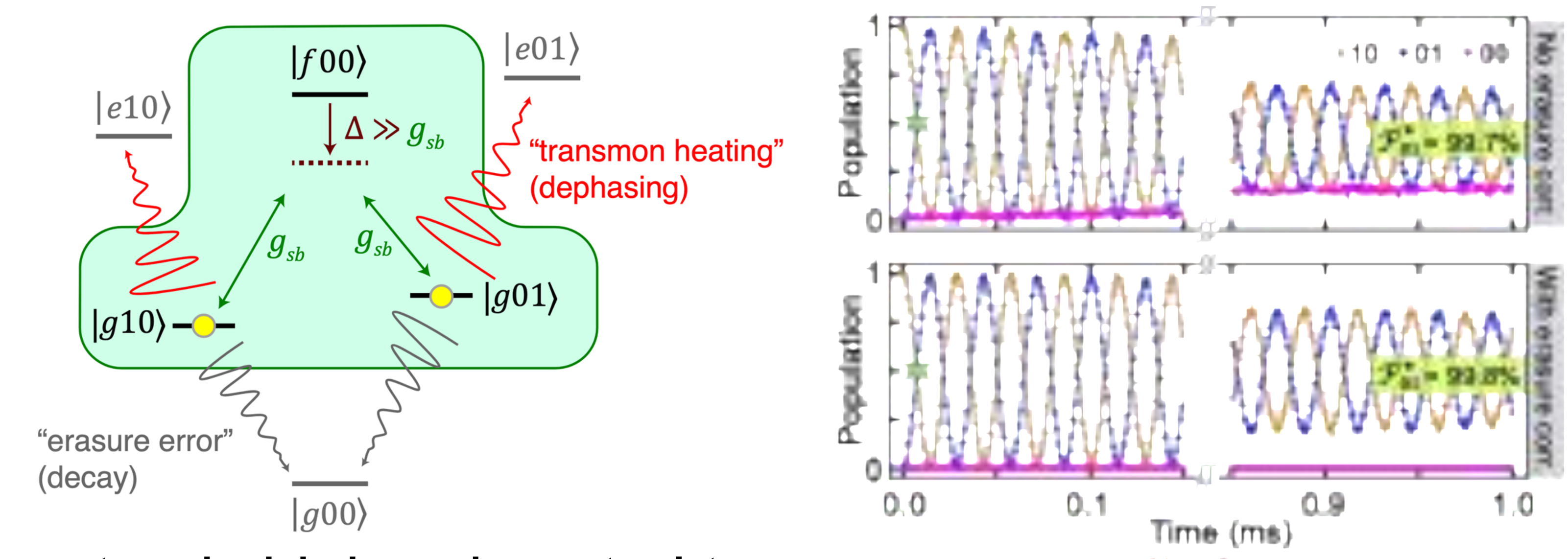
We built a two-cell TESLA-shaped niobium SRF cavity that supports two high-Q modes, "Alice" at 5.8 GHz and "Bob" at 6.9 GHz, both weakly coupled to a single transmon ancilla. The elliptical multi-cell geometry preserves the low surface participation ratio properties of accelerator cavities, with a high geometry factor (~300 Ω) and extremely low surface dielectric participation (~10^{-8}), so that bare single-photon lifetimes of **25.5 ms** (Alice) and **19.3 ms** (Bob). We measure T_1 = **20.6 ms** (Alice) and **15.6 ms** (Bob) and $T_2 \approx$ **21 ms** for both modes after transmon integration. Fock-state lifetimes follow the expected 1/n scaling up to |20⟩, where T_1 remains $\gtrsim$ 1 ms, confirming that large-photon-number states remain long lived and establishing this device as an ultracoherent two-mode platform for multimode bosonic quantum information processing.

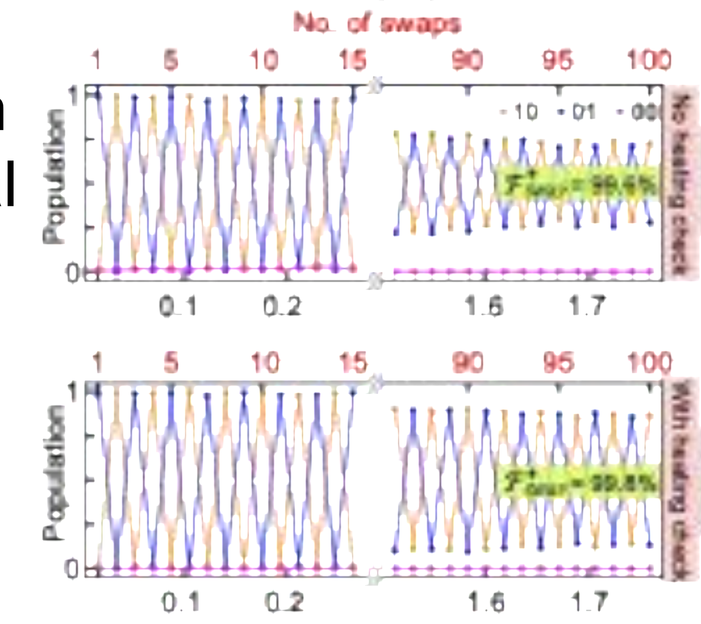
Ancilla Error-resilient Cavity State Preparation



We develop ancilla-error-resilient protocols for preparing high-photon-number Fock states using sideband control. Starting from $|g,n\rangle$, we excite the transmon to $|f,n\rangle$ and drive resonant $|f,n\rangle \leftrightarrow |g,n+1\rangle$ sidebands to climb the Fock ladder, while a fast three-level readout (> 98 % fidelity) monitors the ancilla after every sideband pulse. The measurement outcome reveals ancilla errors, which we correct in real time using transmon π and sideband pulses, forming the sideband feedforward protocol (SFP). Because residual infidelity after SFP is concentrated mostly in $|N-1\rangle$, we apply a parity filter and post-select to suppress these events further. Using SFP and parity filtering, we prepare Fock states up to |20⟩ in both Alice and Bob with fidelities above **95 %**, representing the highest reported fidelities for such large photon numbers in superconducting platforms with only minimal additional time overhead per ladder step.

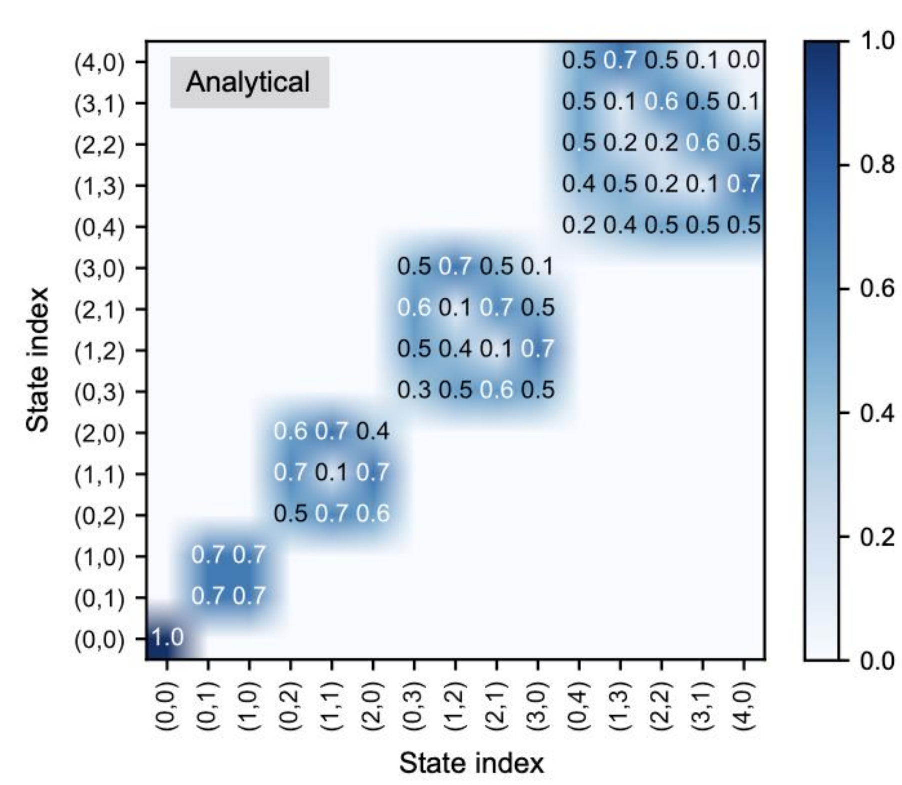
Sideband-mediated Two-mode Entangling Operation





We extend sideband control to implement an entangling operation between Alice and Bob via a virtual Raman beamsplitter (VRBS) interaction. By simultaneously driving the transmon near both $|f,0\rangle \leftrightarrow |g,1\rangle$ sidebands with a common detuning Δ, we virtually populate the $|f00\rangle$ level and engineer an effective beamsplitter Hamiltonian in the single-photon subspace. Starting from $|10\rangle$, we observe coherent oscillations of population between $|01\rangle$ and $|10\rangle$, and extract coherence-limited fidelities of **99.7 %** for a beamsplitter and **99.6 %** for a SWAP. Post-selecting on shots without photon-loss erasures and adding mid-circuit transmon measurements to detect heating events improves the effective fidelity to **99.8 %**.

Outlook: Universal Qudit Control



$$\mathcal{U} = \mathrm{R}_d(\vec{\theta}_0) \otimes \mathrm{R}_d(\vec{\phi}_0) \prod_{i=1}^{N_{\rm block}} \left[\mathrm{VRBS}\ \mathrm{R}_d(\vec{\theta}_i) \otimes \mathrm{R}_d(\vec{\phi}_i)\right]$$

$$\mathrm{CSUM}: \quad |i,j\rangle \longrightarrow |i,(j+i) \bmod d\rangle$$

$$\mathcal{F}^{N_{\rm blocks}}_{\rm CSUM_3} = \{51\%, 88\%, 92\%, 99.1\%, 99.999974\%\}$$

These results pave the way toward universal qudit gates on two-mode cavity platform. Each long-lived cavity mode can encode a high-dimensional qudit in its Fock space, while sideband, SNAP, and ECD operations provide universal single-qudit control, and the VRBS interaction supplies an entangling operation that can be compiled into two-qudit gates, such as the qutrit CSUM. Looking ahead, the two-cell cavity demonstrated here is a natural building block for cascaded random-access quantum memories and interconnected multi-cell TESLA modules, enabling scalable multi-qudit processors based on ultra-high-Q SRF technology.