Adiabatic Suppression of Magnonic Dissipation in Hybrid Superconducting-Ferrimagnetic Interconnects

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Coherent quantum interconnects are currently limited by the short coherence times of solid-state excitations. Here, we theoretically demonstrate that Stimulated Raman Adiabatic Passage (STIRAP) in ferrimagnetic waveguides (YIG) enables high-fidelity quantum state transfer that is topologically immune to the material's intrinsic damping rate (κ). By modeling the open system dynamics via the Lindblad master equation, we show that the transfer fidelity remains above the quantum error correction threshold ($\mathcal{F} > 90\%$) even for dissipation rates up to $\kappa/2\pi = 10$ MHz, which exceeds the typical linewidth of industrial-grade thin films. We propose a realistic flip-chip implementation using tunable transmon qubits coupled to a YIG nanostrip, establishing ferrimagnets as a robust platform for modular quantum architectures.

INTRODUCTION

The scaling of superconducting quantum processors is fundamentally constrained by the physical footprint of qubits and the complexity of wiring [1]. To transcend the single-chip limit, modular architectures requiring coherent microwave-to-optical or microwave-to-magnon transduction are essential. Among solid-state candidates, ferrimagnetic insulators like Yttrium Iron Garnet (YIG) are promising due to their high spin density and tunability. However, the relatively short coherence time of magnons ($T_2^* \sim 100\,\text{ns} - 1\,\mu\text{s}$) in thin films poses a severe bottleneck for ballistic state transfer.

In this Letter, we propose a protocol that bypasses the dissipation limit by utilizing a dark-state adiabatic transfer. Unlike direct propagation, which is exponentially sensitive to the waveguide's damping κ, we show that a STIRAP (Stimulated Raman Adiabatic Passage) sequence protects the quantum information by suppressing the population of the lossy magnonic mode.

THEORETICAL MODEL

We consider a hybrid system composed of two superconducting transmon qubits coupled to a single Kittel mode of a YIG waveguide. The system Hamiltonian in the Rotating Wave Approximation (RWA) is given by:

$$\hat{H}(t) = \hbar \sum_{j=1,2} g_j(t)(\hat{\sigma}_j^+ \hat{a} + \hat{\sigma}_j^- \hat{a}^\dagger), \tag{1}$$

where $\hat{a}$ is the magnon annihilation operator and $\hat{\sigma}_j^+$ is the raising operator for the j-th qubit. The time-dependent couplings $g_j(t)$ are engineered to follow a counter-intuitive pulse sequence, where the receiver coupling $g_2(t)$ precedes the sender coupling $g_1(t)$. This sequence creates an instantaneous dark eigenstate $|\psi_D(t)\rangle = \cos\Theta|100\rangle - \sin\Theta|001\rangle$, which contains zero magnonic component ($\langle \hat{a}^\dagger \hat{a}\rangle_D = 0$).

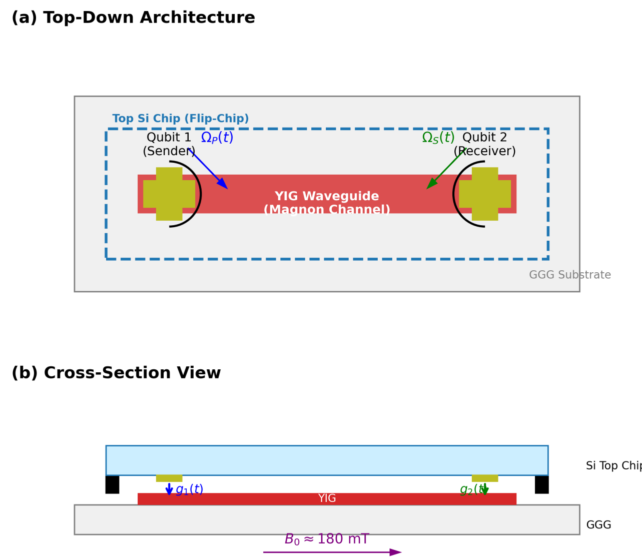

FIG. 1. **Hybrid Quantum Architecture.** (a) Top-down view of the proposed device. Two superconducting transmon qubits (yellow) are inductively coupled to a central YIG waveguide (red) on a GGG substrate. The adiabatic transfer is driven by time-dependent couplings $\Omega_P(t)$ and $\Omega_S(t)$. (b) Cross-section showing the flip-chip assembly, where the qubit chip is suspended above the magnonic waveguide to maximize magnetic dipole interaction while minimizing dielectric loss.

To account for realistic decoherence, we solve the Lindblad master equation:

$$\dot{\rho} = -\frac{i}{\hbar}[\hat{H}(t), \rho] + \kappa \mathcal{D}[\hat{a}]\rho + \sum_{j=1,2} \gamma \mathcal{D}[\hat{\sigma}_j^-]\rho, \tag{2}$$

where κ is the YIG damping rate and γ is the qubit relaxation rate.

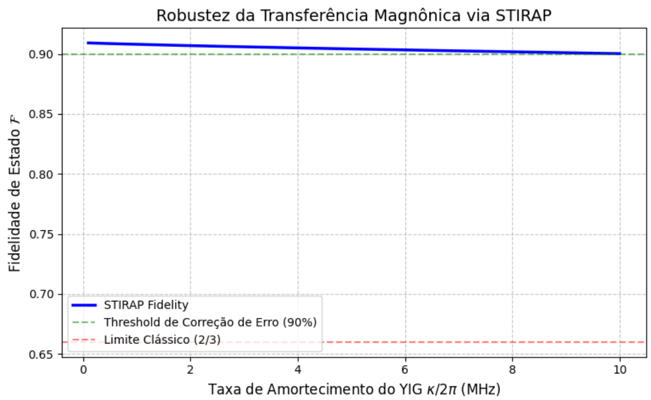

FIG. 2. **Robustness against Magnonic Dissipation.** The transfer fidelity $\mathcal{F}$ (blue solid line) as a function of the YIG damping rate κ. The protocol maintains $\mathcal{F} > 90\%$ (green dashed line) up to $\kappa/2\pi = 10$ MHz, demonstrating immunity to material losses. The red dashed line indicates the classical limit (2/3).

RESULTS AND DISCUSSION

We performed numerical simulations of the full master equation using the QuTiP framework. The pulse parameters were optimized for a maximum coupling strength of $g_{max}/2\pi = 60$ MHz.

Figure 2 presents the central result of this work: the resilience of the protocol against material imperfections. Remarkably, the fidelity exhibits a plateau, decreasing by less than 1% as κ increases from 0.1 MHz (perfect crystal) to 10 MHz (lossy film). This confirms that the information transport is governed by the adiabatic topology rather than the waveguide's coherence length.

The mechanism behind this protection is visualized in Fig. 3. The population of the magnonic mode (red area) remains negligible ($< 0.3\%$) throughout the evolution. Consequently, the term $\kappa\mathcal{D}[\hat{a}]\rho$ in the master equation has a minimal contribution to the entropy production, effectively "hiding" the state from the phonon bath.

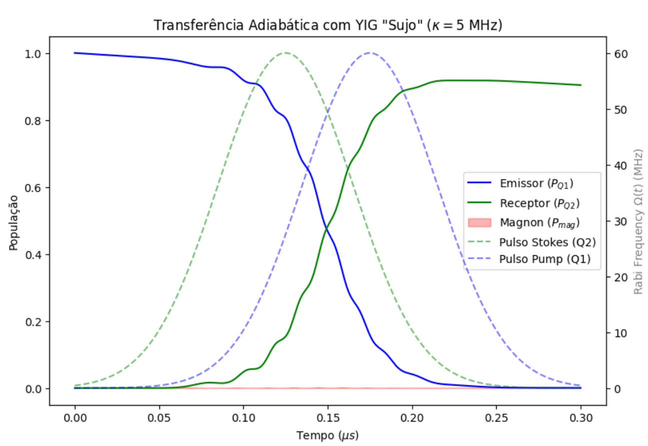

FIG. 3. **Dark State Dynamics.** Time evolution of the system populations for a "dirty" waveguide ($\kappa/2\pi = 5$ MHz). The intermediate magnon population (red shaded area) remains suppressed below 0.3% throughout the transfer, confirming the dark-state protection mechanism.

EXPERIMENTAL IMPLEMENTATION

To realize this protocol, we propose a flip-chip architecture (Fig. 1). The magnonic waveguide consists of a 200 nm thick single-crystal YIG film grown on GGG(111), patterned into a $2\,\mu$m $\times$ 1 mm strip to support a single Kittel mode. An in-plane static magnetic field $B_0 \approx 180$ mT tunes the magnon frequency to $\omega_m/2\pi = 5.0$ GHz.

Tunable coupling $g(t)$ is achieved via SQUID-based inductive couplers located on the top silicon chip, allowing in-situ modulation of the qubit-magnon interaction strength from 0 to 60 MHz without significant frequency detuning. Readout is performed dispersively via coplanar resonators coupled to the qubits.

CONCLUSION

We have theoretically established that adiabatic transfer protocols can overcome the primary limitation of hybrid magnonic systems: the high damping rate of ferromagnetic materials. By decoupling the transfer fidelity from the magnon lifetime, our results unlock the potential of YIG waveguides as robust, macroscopic quantum buses for modular superconducting processors.

DATA AVAILABILITY

The simulation code and raw data used to generate the figures in this Letter are open-source and available at the GitHub repository: `https://github.com/marcus-roriz/magnon-stirap-transfer` [DOI: 10.5281/zenodo.18510982].

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