Precise Raman Control of Spinor Matterwave with Nanosecond Composite Biased Rotations

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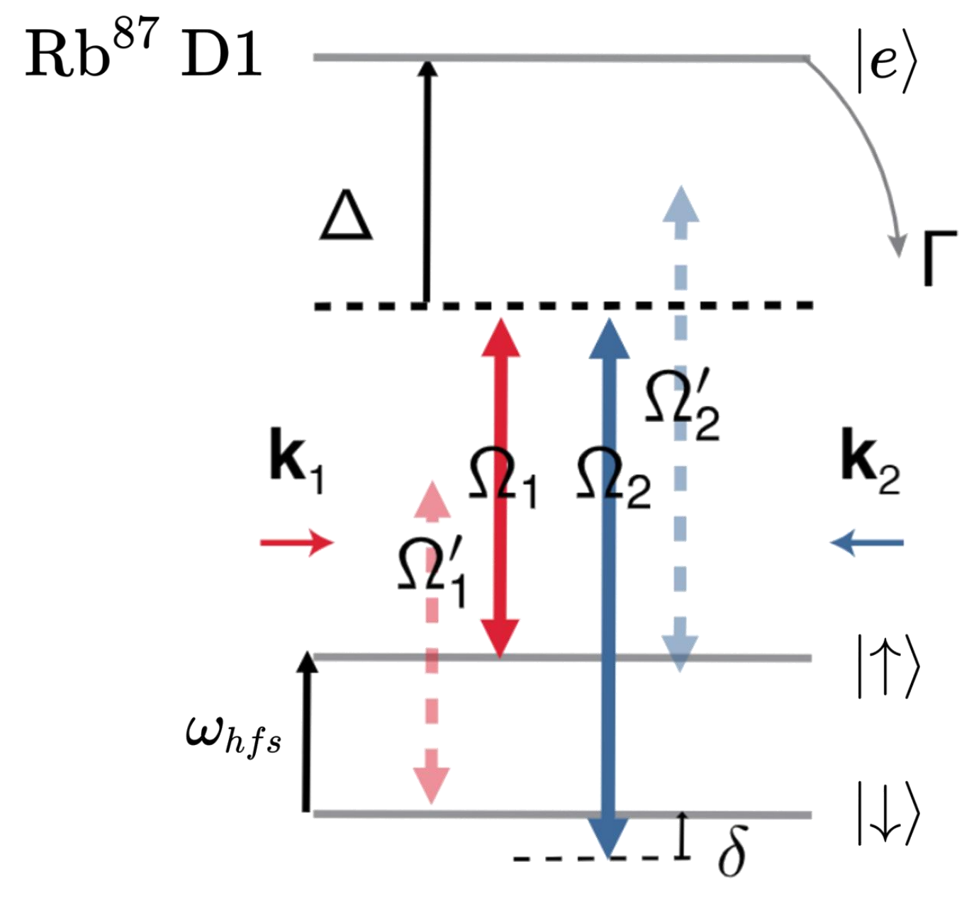
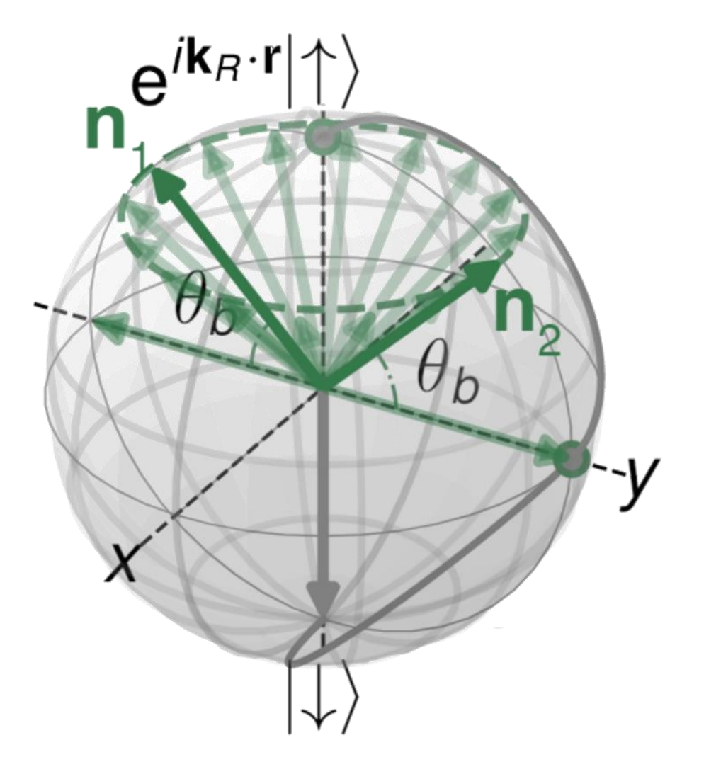
I. Introduction

We experimentally demonstrate precise Raman matterwave control at an intermediate single-photon detuning $\Delta = O(\omega_{hfs})$, where a balance between the optical power efficiency with the requirements on the control speed and the suppression of excited-state dynamics can be adjusted. The method is based on composite biased rotation[1] that exploits the proportionality between the traditionally "unwanted" light shift δ with the Raman coupling Ω_R. At $\Delta \approx 4\omega_{hfs}$, mesoscopic samples of 10^5 ^{87}Rb atoms are uniformly controlled, within tens of nanoseconds, near a laser focus with merely ~10 mW power. The control is fast enough to be immune to low-frequency noises, so our system can be accurately modeled. The $\mathcal{F} > 99.2\%$ fidelity is estimated with standard single-qubit QPT[2] and RB[3]. Our work suggests highly precise spinor matterwave controls are achievable for large atomic samples with moderate laser power, even in noisy environment.



'Composite Biased Rotations ' (CP-BR)

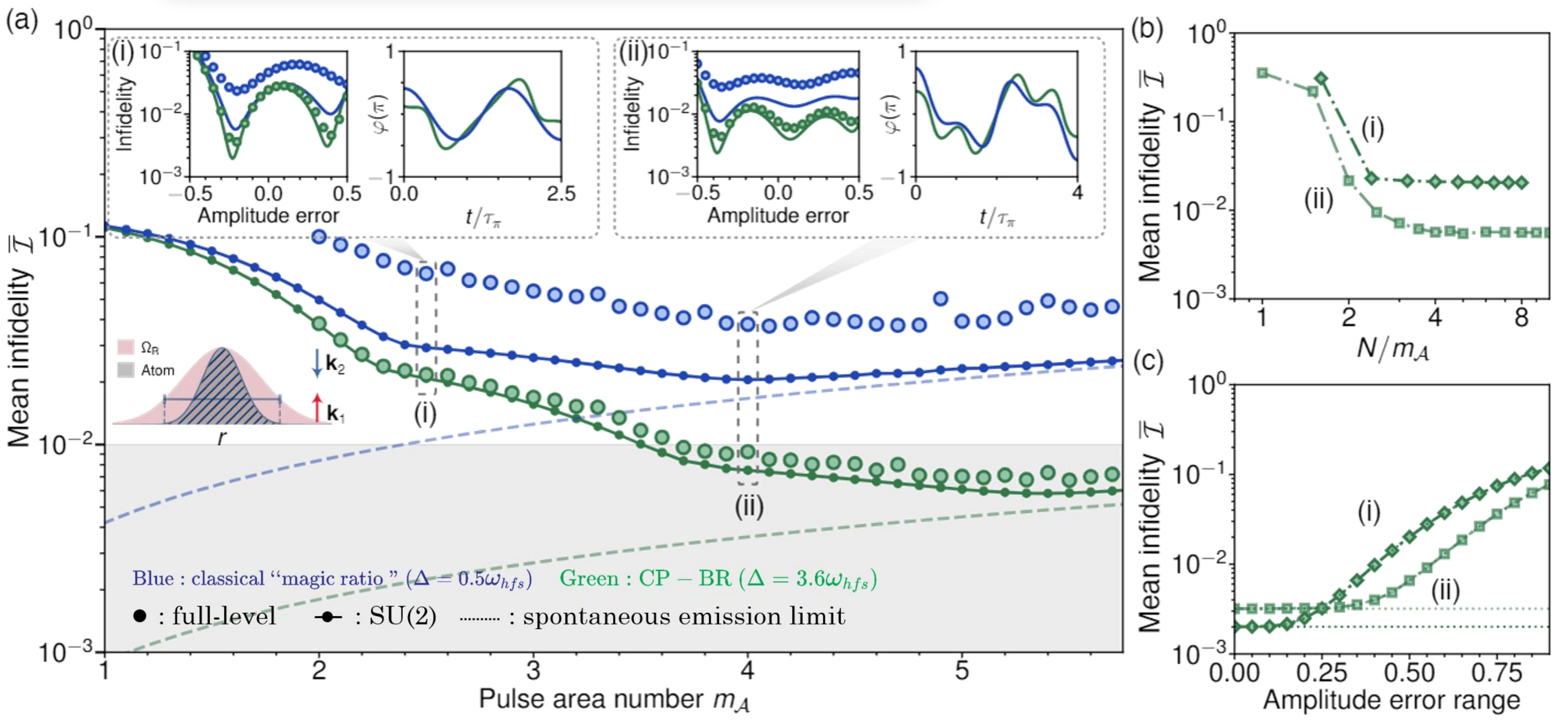


II. Theoretical Model

$$H = -\frac{1}{2}\hbar\delta\sigma_z + \frac{1}{2}\hbar|\Omega_{\rm R}|(\sigma_x\cos\varphi + \sigma_y\sin\varphi)$$

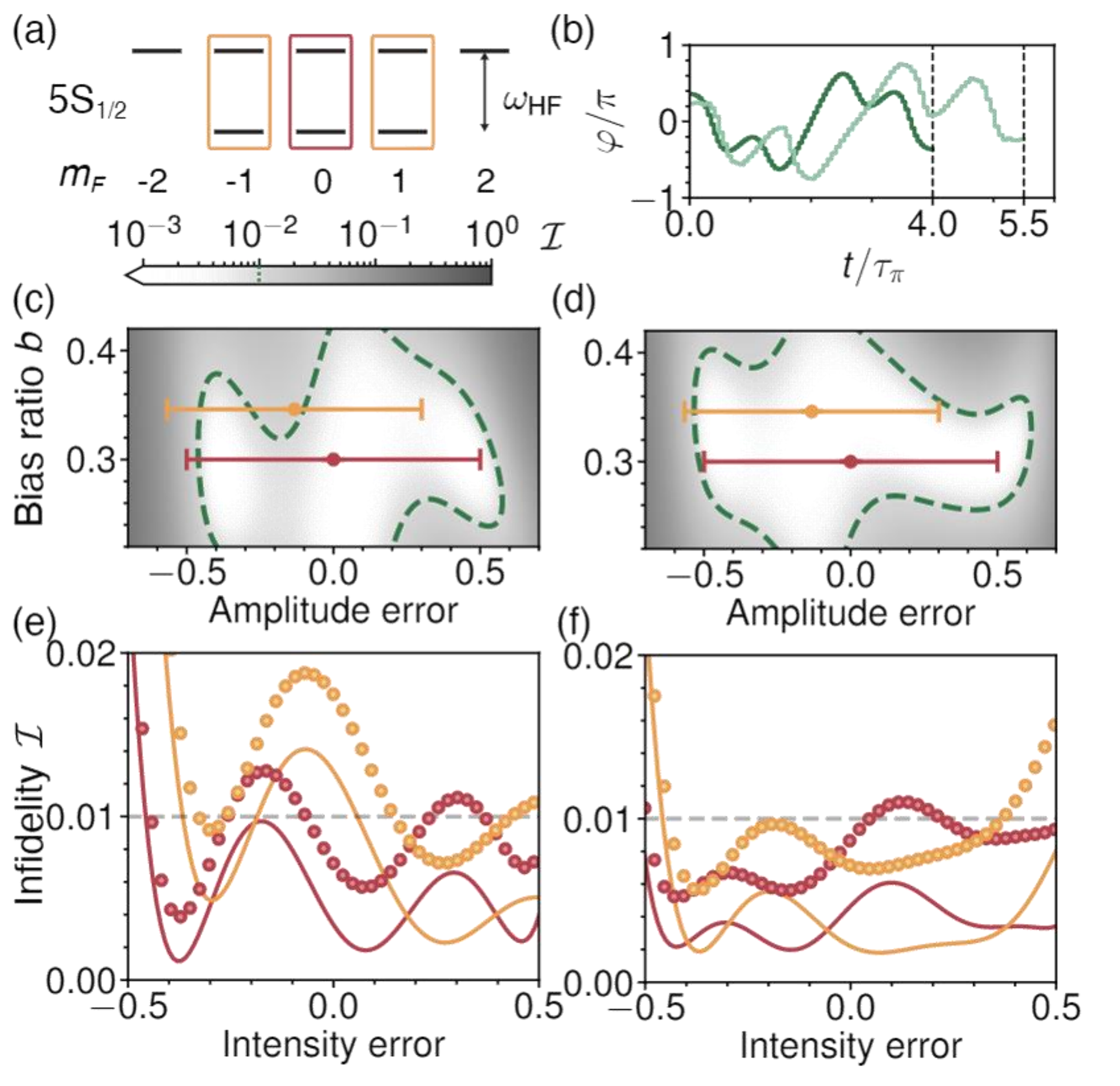
$$\delta = \frac{|\Omega_1|^2}{4\Delta} + \frac{|\Omega_2'|^2}{4(\Delta-\omega_{\rm HF})} - \frac{|\Omega_2|^2}{4\Delta} - \frac{|\Omega_1'|^2}{4(\Delta+\omega_{\rm HF})}$$

$$\theta_b = \tan^{-1}(\delta/|\Omega_{\rm R}|)$$



Blue : classical "magic ratio " ($\Delta = 0.5\omega_{hfs}$) Green : CP − BR ($\Delta = 3.6\omega_{hfs}$)
● : full-level -●- : SU(2) ⋯⋯ : spontaneous emission limit

- Multiple Zeeman-spins



Intensity-error immunity supports high-fidelity matterwave control of multiple Zeeman spinors in parallel.

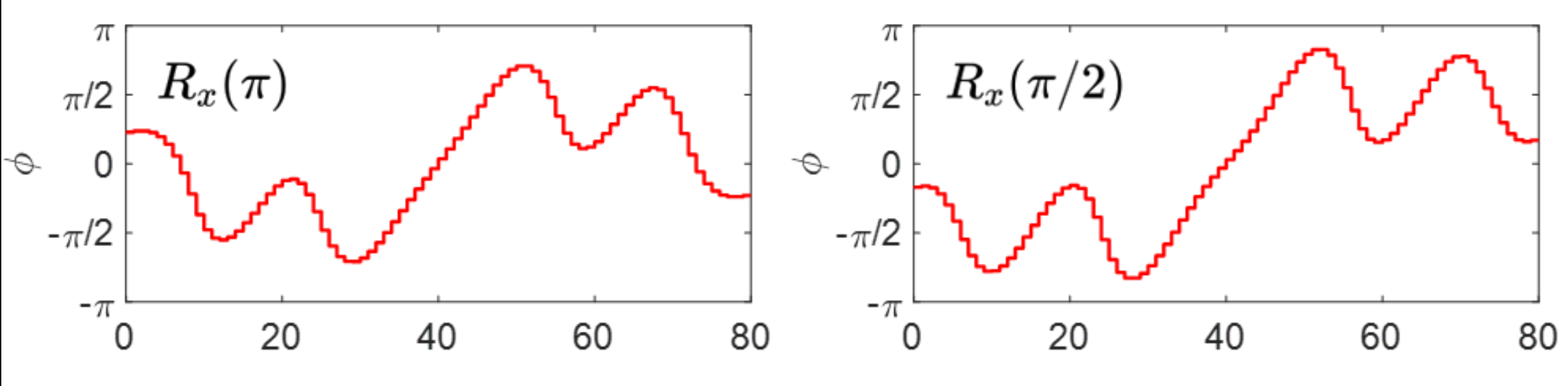
III. Pulse shaping

- Optimization algorithm-**GRAPE**

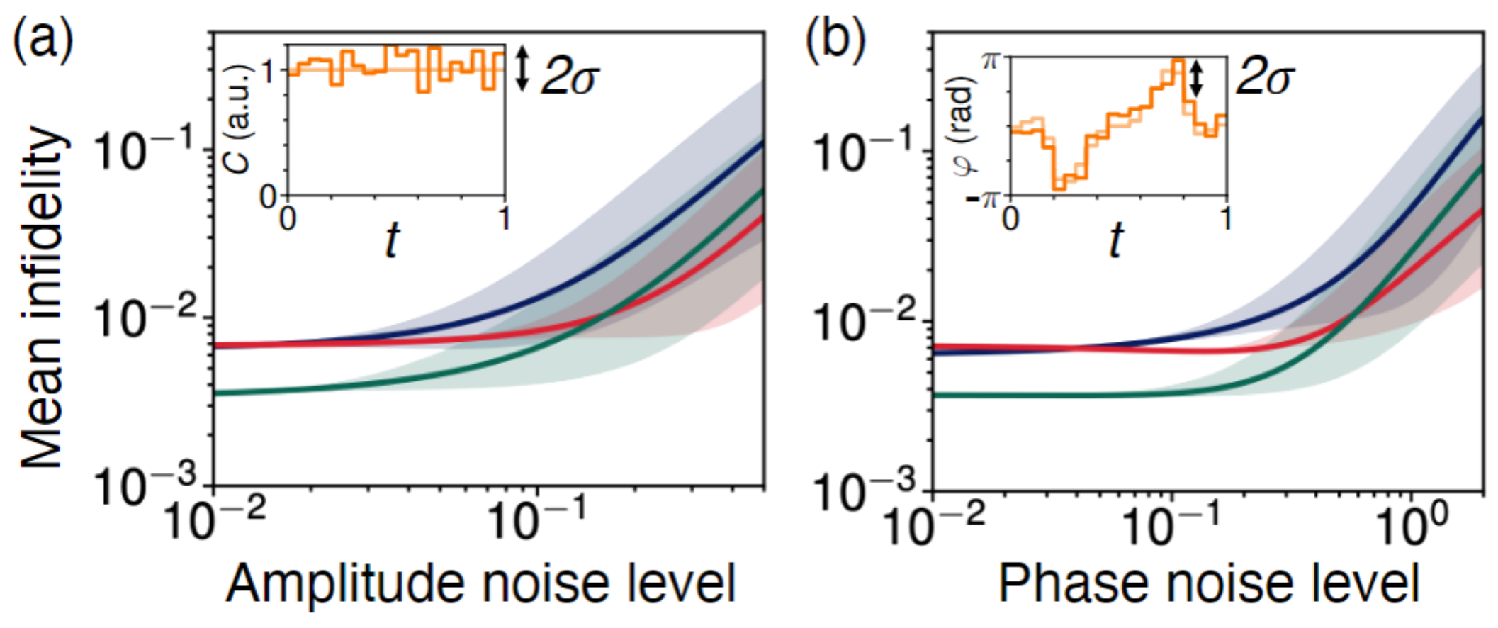
SU(2) rotation operator: $U(\mathcal{A},b,\varphi) = \mathbf{1}\cos\frac{\tilde\phi}{2} - i\sin\frac{\tilde\phi}{2}\frac{\sigma_x\cos\varphi + \sigma_y\sin\varphi + b\sigma_z}{\sqrt{1+b^2}}$

Gate fidelity: $\mathcal{F} = \frac{1}{6}\sum_{j=1}^{6}|\langle\psi_j|U^\dagger\tilde U|\psi_j\rangle|^2$

Gradient: $g_i = -\frac{\partial\mathcal{F}}{\partial\tilde U}\frac{\partial\tilde U}{\partial\varphi_i}$ $\frac{\partial\tilde U}{\partial\varphi_i} = \tilde U_N\cdots\tilde U_{i+1}\frac{\partial\tilde U_i}{\partial\varphi_i}\tilde U_{i-1}\cdots\tilde U_1$



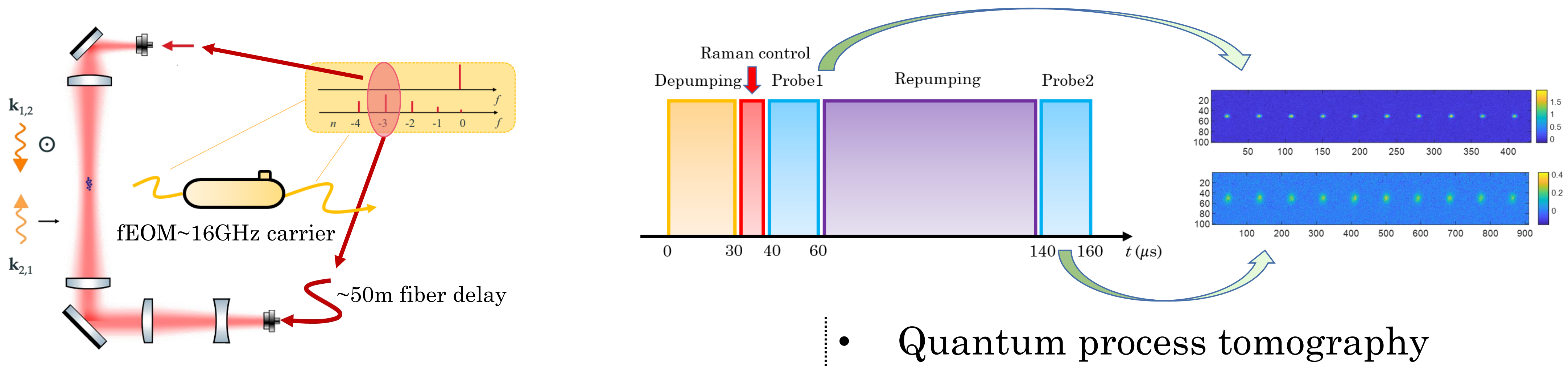
- Pulse noise resilience



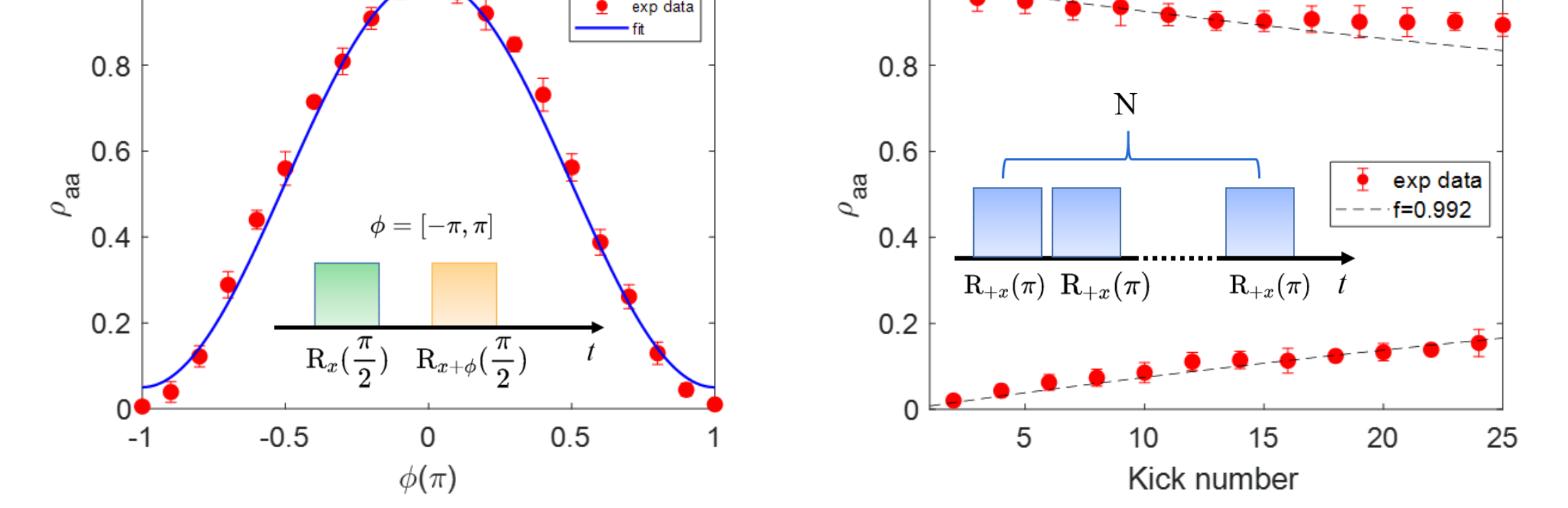
Blue: N = 20, A = 4π, Red: N = 80, A= 4 π, Green: N= 80,A = 5.5π

IV. Experimental setup and results

- The experimental setup and measurement procedure

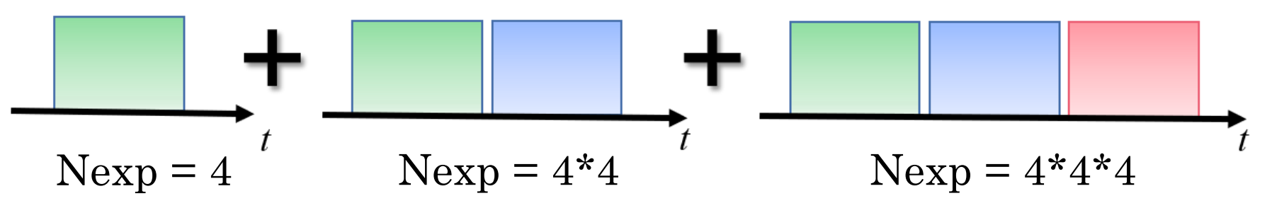


- Ramsey Interferometry and Multiple π-Gates

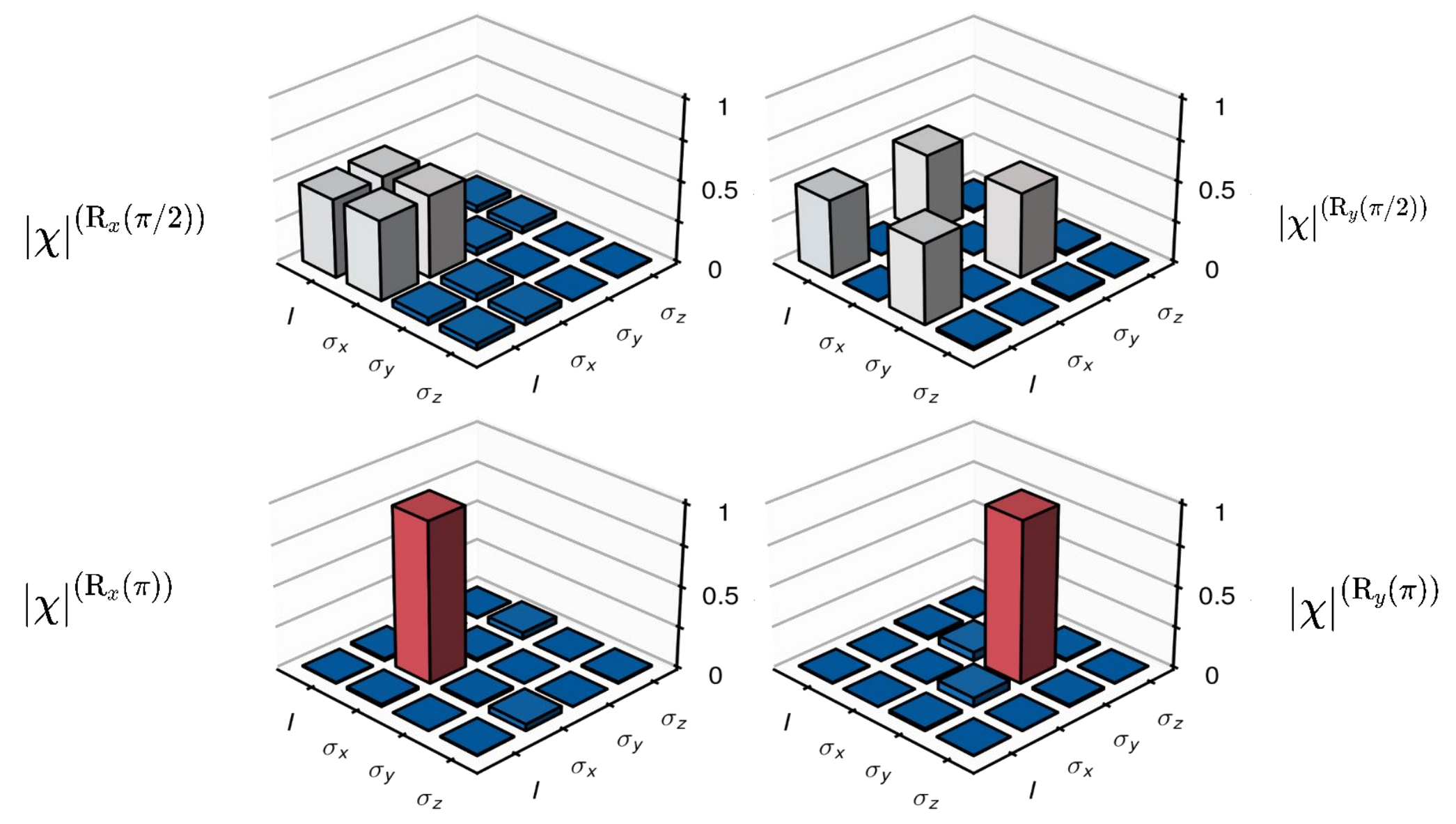


- Quantum process tomography

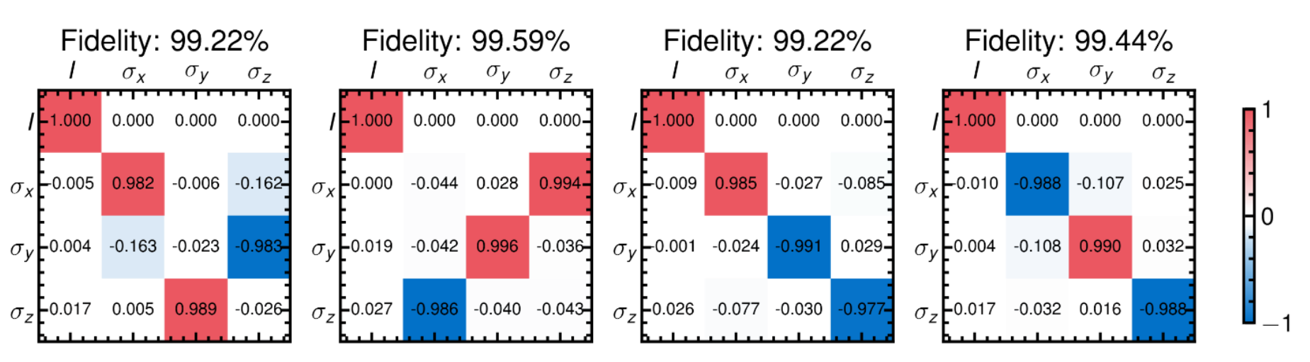
Gates base : $\{\,\mathrm{R}_{+x}(\pi/2), \mathrm{R}_{+y}(\pi/2), \mathrm{R}_{+x}(\pi), \mathrm{R}_{+y}(\pi)\,\}$



Gate χ − matrix : $\Lambda(\rho) = \sum_{j,k=1}^{d^2}\chi_{jk}P_j\rho P_k$ $P_j \in \mathcal{P}^{\otimes n}, \mathcal{P} = \{I,\sigma_x,\sigma_y,\sigma_z\}$



Pauli transfer matrix : $(R_\Lambda)_{ij} = \frac{1}{d}\mathrm{Tr}\{P_i\Lambda(P_j)\}$



	I	σ_x	σ_y	σ_z
I	1.000	0.000	0.000	0.000
σ_x	-0.005	0.982	-0.006	-0.162
σ_y	-0.004	-0.163	-0.023	-0.983
σ_z	-0.017	0.005	0.989	-0.026

	I	σ_x	σ_y	σ_z
I	1.000	0.000	0.000	0.000
σ_x	-0.000	-0.044	0.028	0.994
σ_y	-0.019	-0.042	0.996	-0.036
σ_z	-0.027	-0.986	-0.040	-0.043

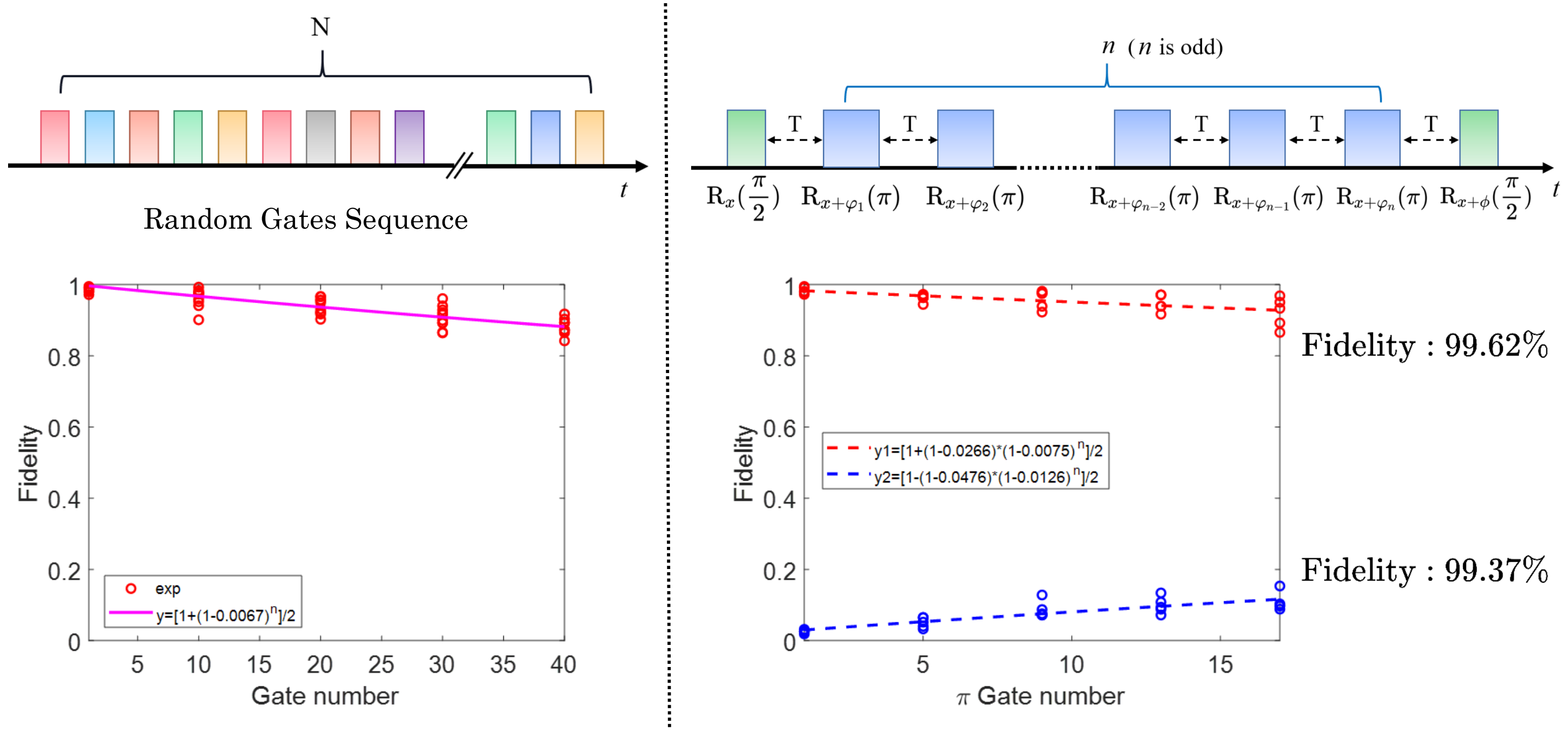
	I	σ_x	σ_y	σ_z
I	1.000	0.000	0.000	0.000
σ_x	-0.009	0.985	-0.027	-0.085
σ_y	-0.001	-0.024	-0.991	0.029
σ_z	-0.026	-0.077	-0.030	-0.977

	I	σ_x	σ_y	σ_z
I	1.000	0.000	0.000	0.000
σ_x	-0.010	-0.988	-0.107	0.025
σ_y	-0.004	-0.108	0.990	0.032
σ_z	-0.017	-0.032	0.016	-0.988

- Randomized benchmarking and dynamic decoupling[2,3]

Gates base : $\{\,\mathrm{R}_{\pm x}(\pi/2),\ \mathrm{R}_{\pm y}(\pi/2),\ \mathrm{R}_{\pm x}(\pi)\ ,\mathrm{R}_{\pm y}(\pi)\}$

π Gates base : $\{\,\mathrm{R}_{\pm x}(\pi)\ ,\ \mathrm{R}_{\pm y}(\pi)\}$



Fidelity : 99.62%

Fidelity : 99.37%

V. Discussions

- The 99.2% fidelity is less than the $\mathcal{F} = 99.7\%$ theoretical limit, likely due to digital noise in the waveforms (to be suppressed with new technology).
- Doubling Δ and laser power together lead to $\mathcal{F}\sim$ 99.9%.
- Toward a practical large area atom interferometer for wideband, noise-immune inertial sensing.
- Scaling-up the Raman control for advanced quantum information processors.

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VI. Reference

[1] QIU L, YUAN H, WU S. PHYSICAL REVIEW RESEARCH 5, 043094 (2023) High-fidelity Raman matterwave control by composite biased rotations[J].
[2] GREENBAUM D. Introduction to Quantum Gate Set Tomography[J]. Quantum Physics,arXiv, 2015.
[3] KNILL E, LEIBFRIED D, REICHLE R, et al. Randomized Benchmarking of Quantum Gates[J].