

20251021 mini colloquium

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Passive Superconducting Circulator on a Chip

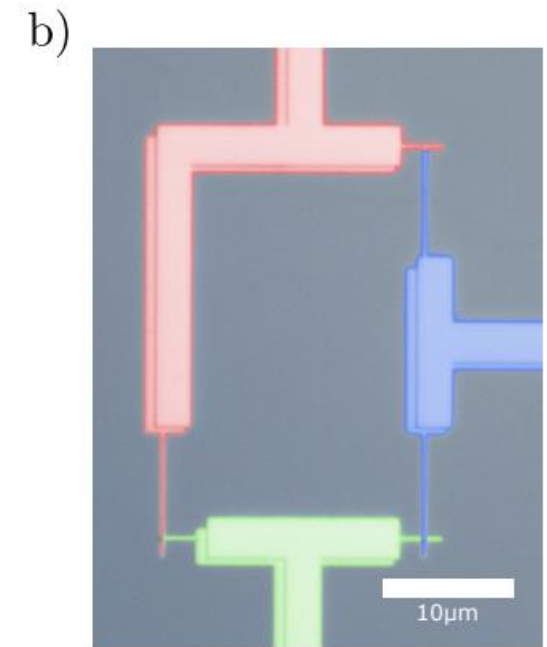
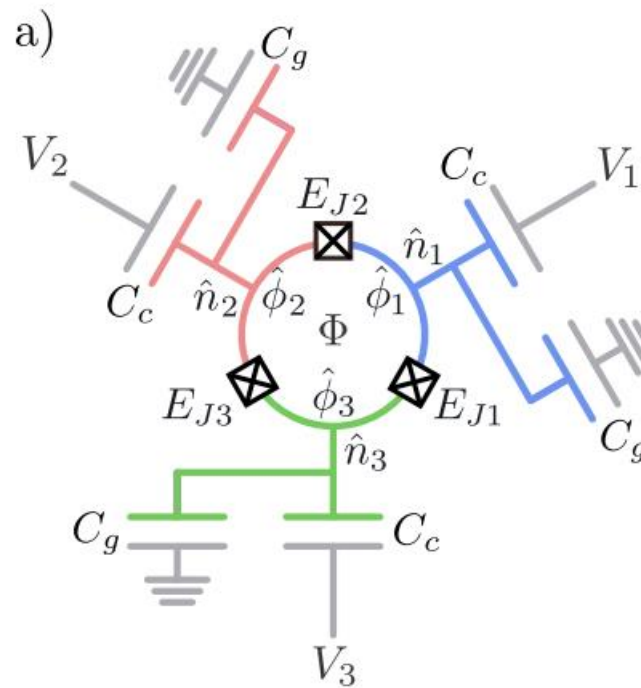
Background and Purpose

- Microwave circulator utilizing ferrite components
 - A strong magnetic field
 - Too large to be integrated
 - External drive

→ passive, on-chip circulator without using ferrite

Devise design

- DC bias voltage V_i
- An external flux Φ



- Hamiltonian

$$\hat{H} = (2e)^2 (\hat{\mathbf{n}} - \mathbf{n}_g) \mathbb{C}^{-1} (\hat{\mathbf{n}} - \mathbf{n}_g) - \sum_{i=1}^3 E_{Ji} \cos(\widehat{\phi_i} - \widehat{\phi_{i+1}} - \frac{1}{3} \phi)$$

Theoretical model

- Hamiltonian

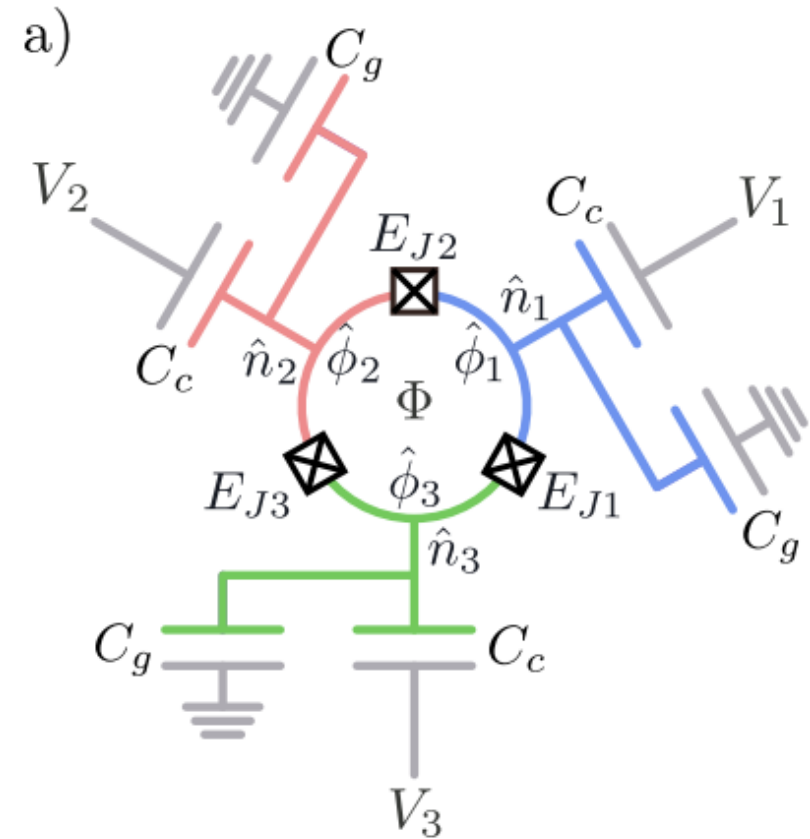
$$\hat{H} = (2e)^2 (\hat{\mathbf{n}} - \mathbf{n}_g) \mathbb{C}^{-1} (\hat{\mathbf{n}} - \mathbf{n}_g) - \sum_{i=1}^3 E_{Ji} \cos(\hat{\phi}_i - \hat{\phi}_{i+1} - \frac{1}{3} \phi)$$

\hat{n} : the charge operator

n_g : the bias charge

$\hat{\phi}_i$: the superconductive phase

$$\phi = \frac{2\pi\Phi}{\Phi_0}$$



Theoretical model

- The scattering matrix S_{ij}

$$S_{ij} = \delta_{ij} - \sum_{k=1,2,\dots} \frac{\Gamma \langle k | \hat{n}_j | 0 \rangle \langle 0 | \hat{n}_i | k \rangle}{i\Delta\omega_k + \Gamma_k/2},$$

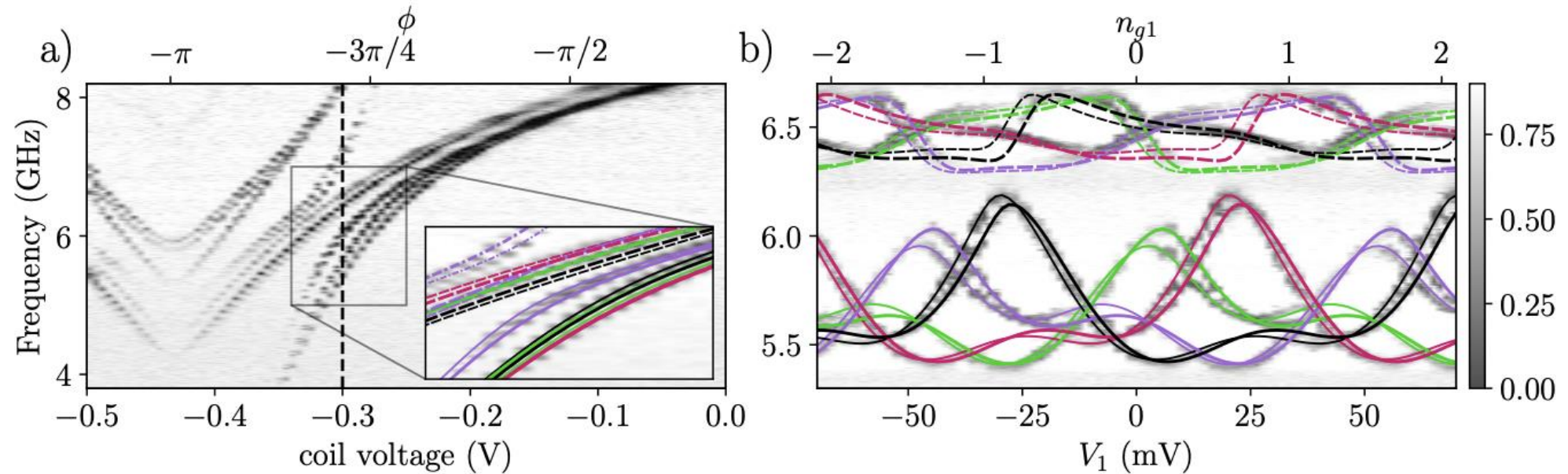
$|k\rangle$: excited states

$\Delta\omega_k$: the detuning of the excited eigenenergy

Γ : the coupling strength

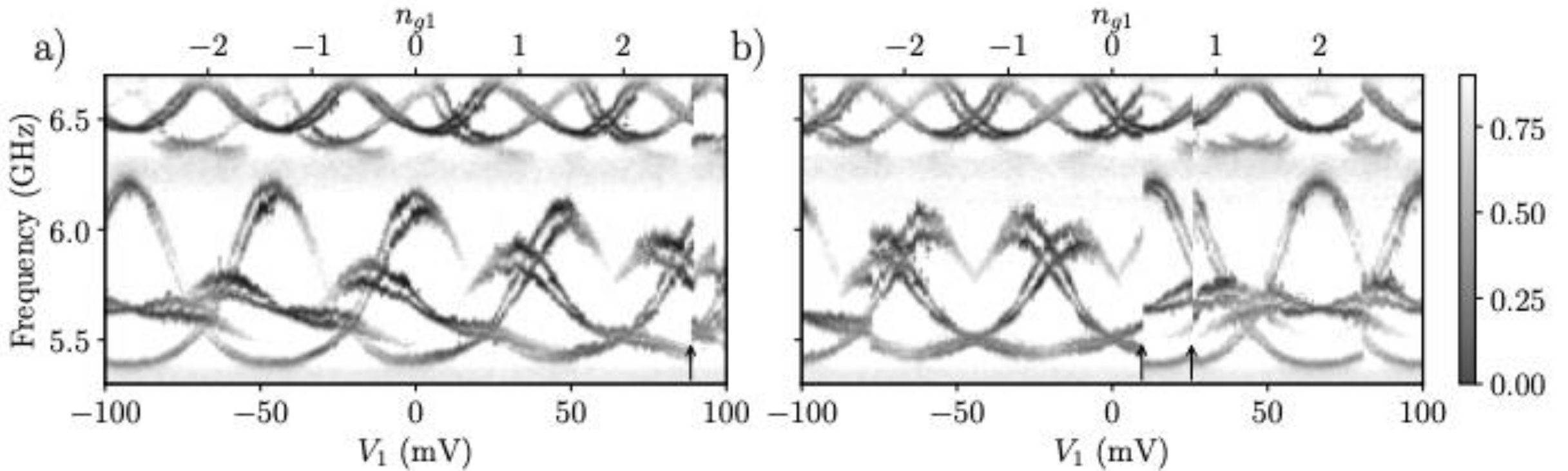
Γ_k : the decay rate

Simulations and result (fig.2)



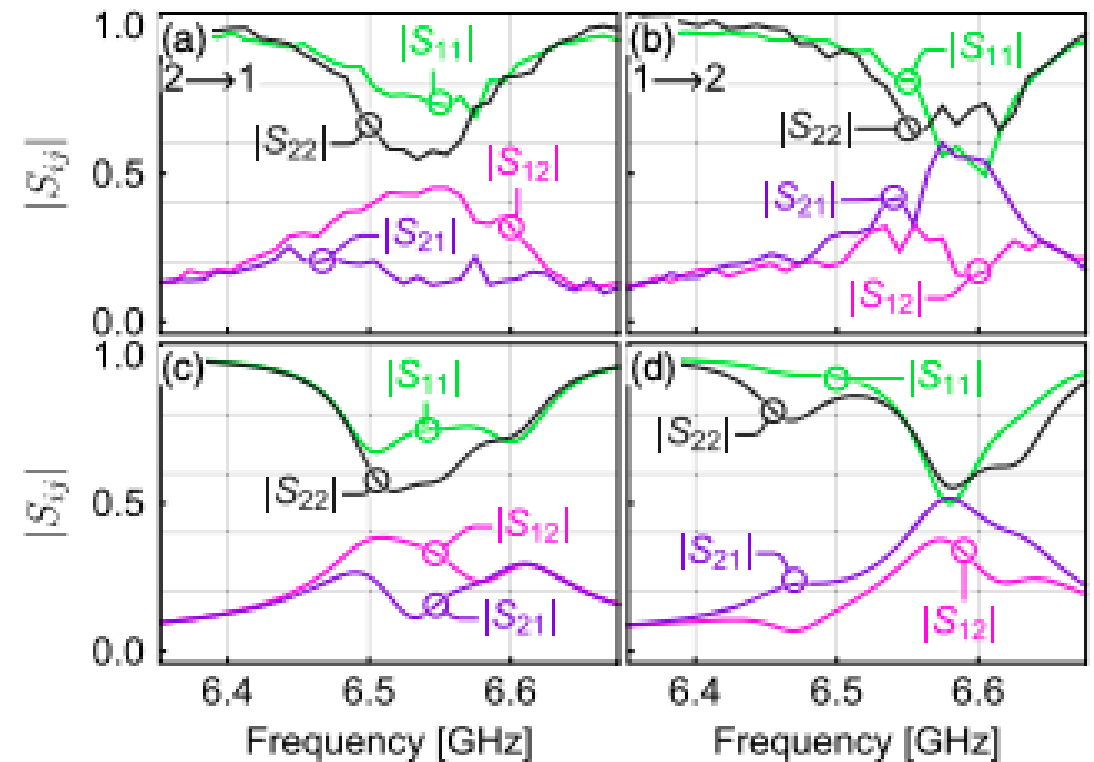
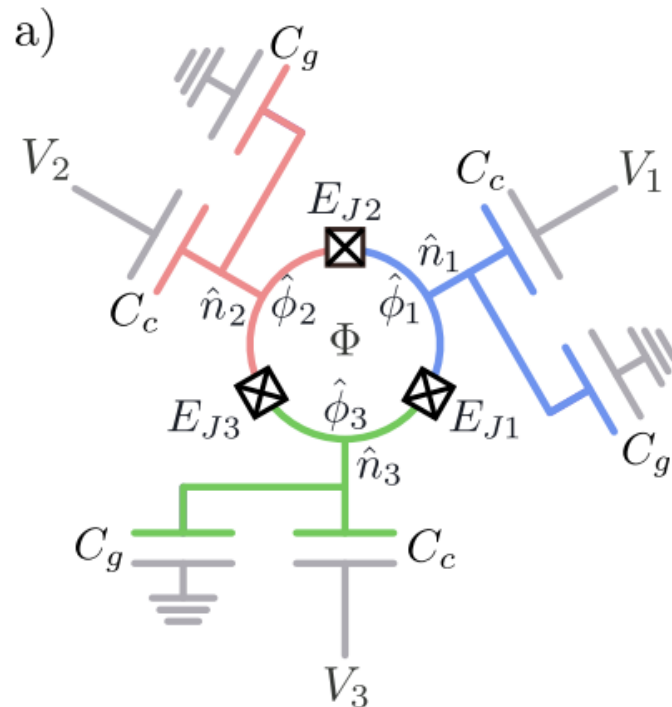
- Coler : quasiparticle configurations
- Line types : transition frequencies

Periodic dependence on applied charge bias



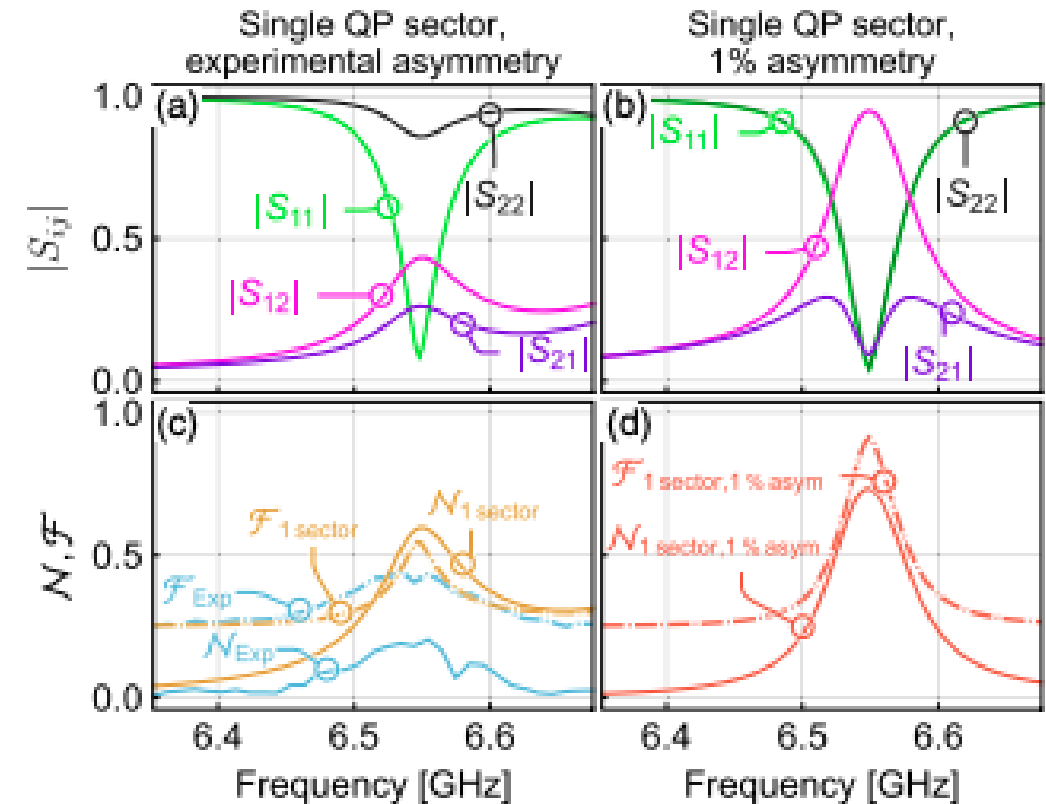
S-matrix elements for two different charge-bias configurations. (fig.3)

- The non-reciprocity can be changed by gate bias V_i .



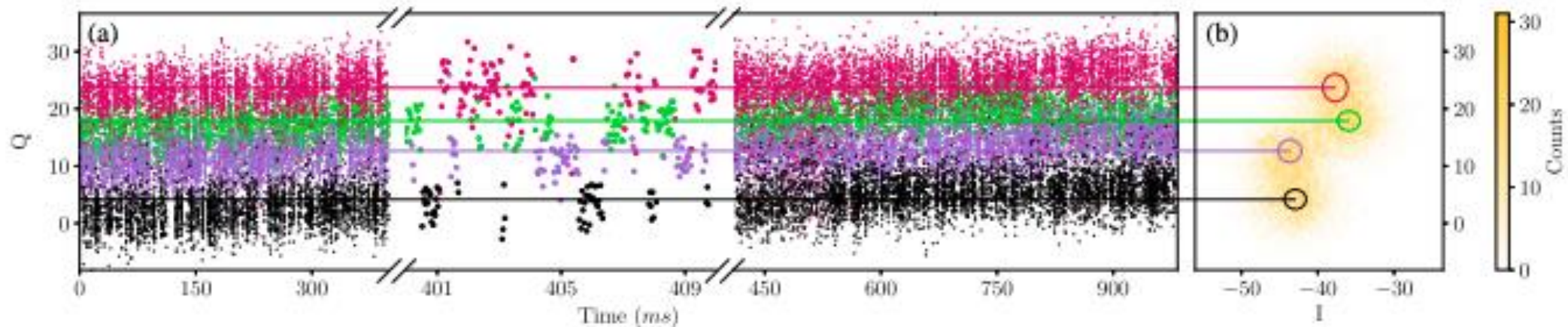
Simulation of Asymmetry(fig.4)

- (a) Asymmetry in this experiment
- (b) 1% asymmetry
- (c) non-reciprocity and fidelity in this experiment
- (d) 1% asymmetry



Detection of Quasiparticle Tunneling Using Hidden Markov Models(fig.5)

- Freq : 6.709GHz, $\phi=1.9$
- identify the four quasi-particle states with HMM
- Time vs Re(S11), Im(S11) vs Re(S11)
- lifetime of the quasi-particle sector : $\sim 200\mu\text{s}$.

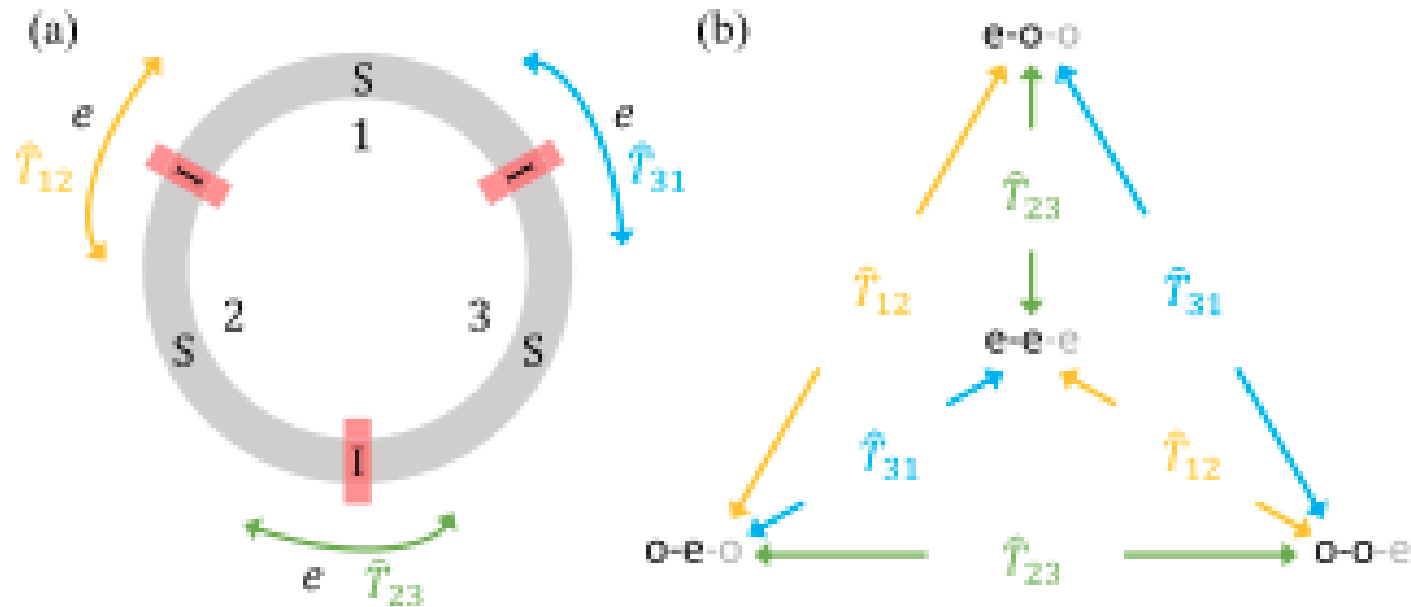


Summary

- First demonstration of passive superconducting circulator operation.
- Non-reciprocity is tunable by changing charge bias and magnetic flux.
- High-fidelity operation expected by reducing junction asymmetry and quasiparticle density.

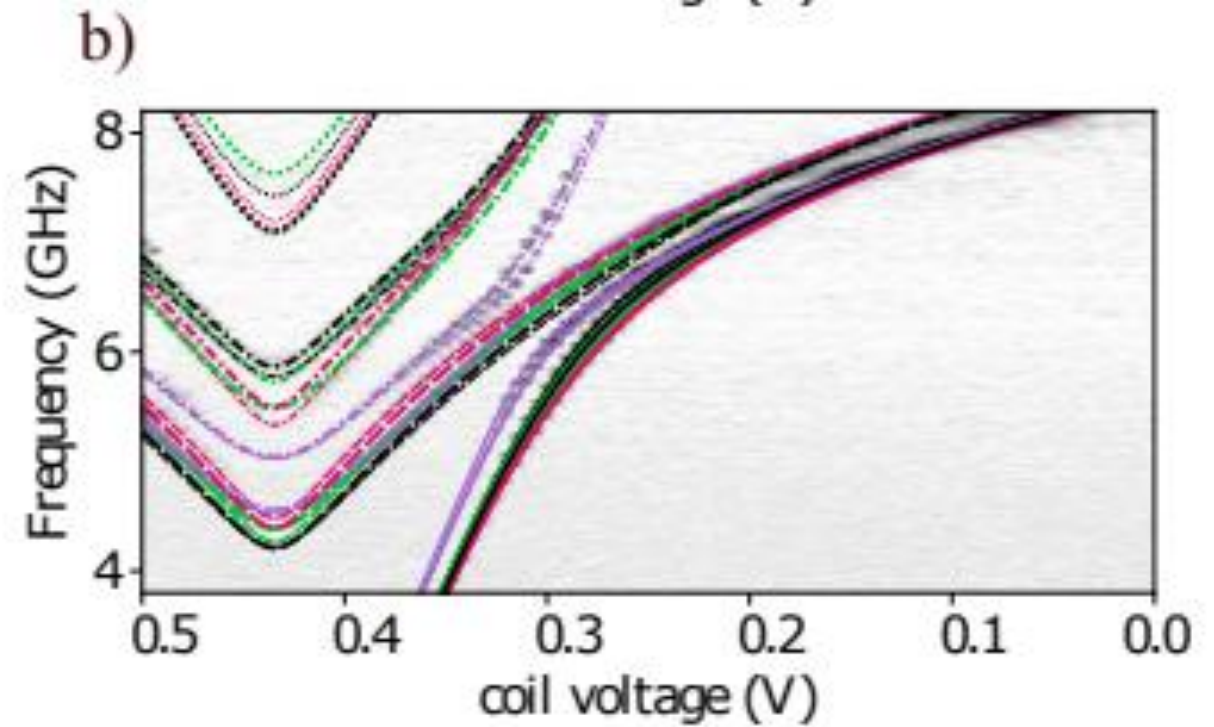
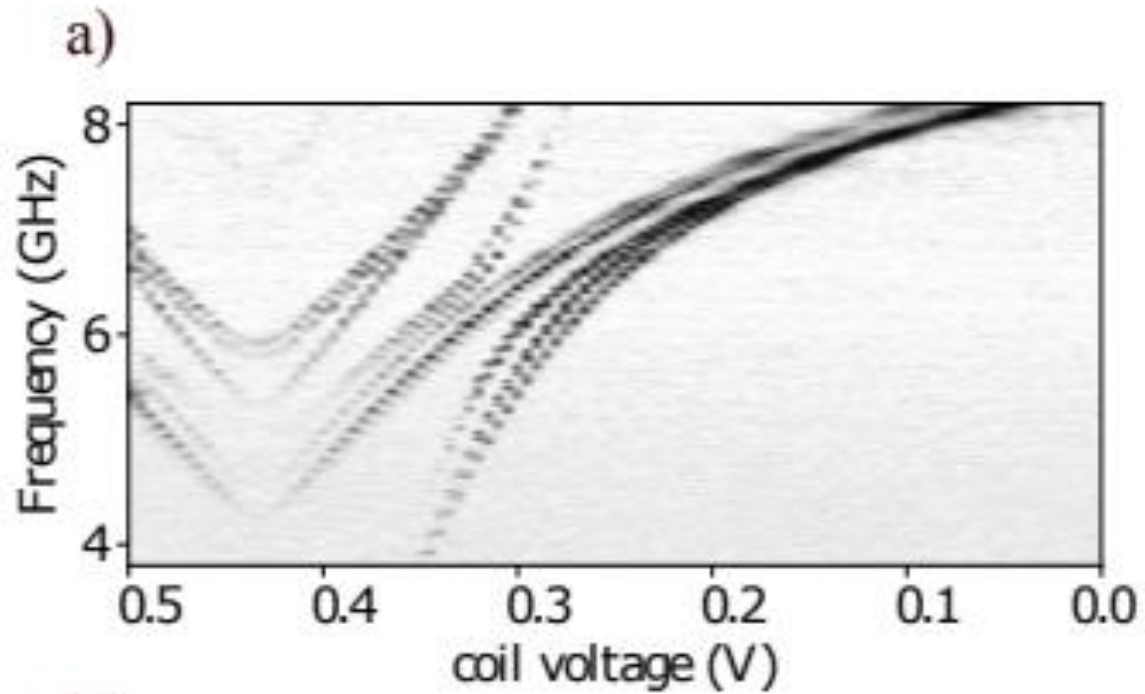
Back up

Charge parity

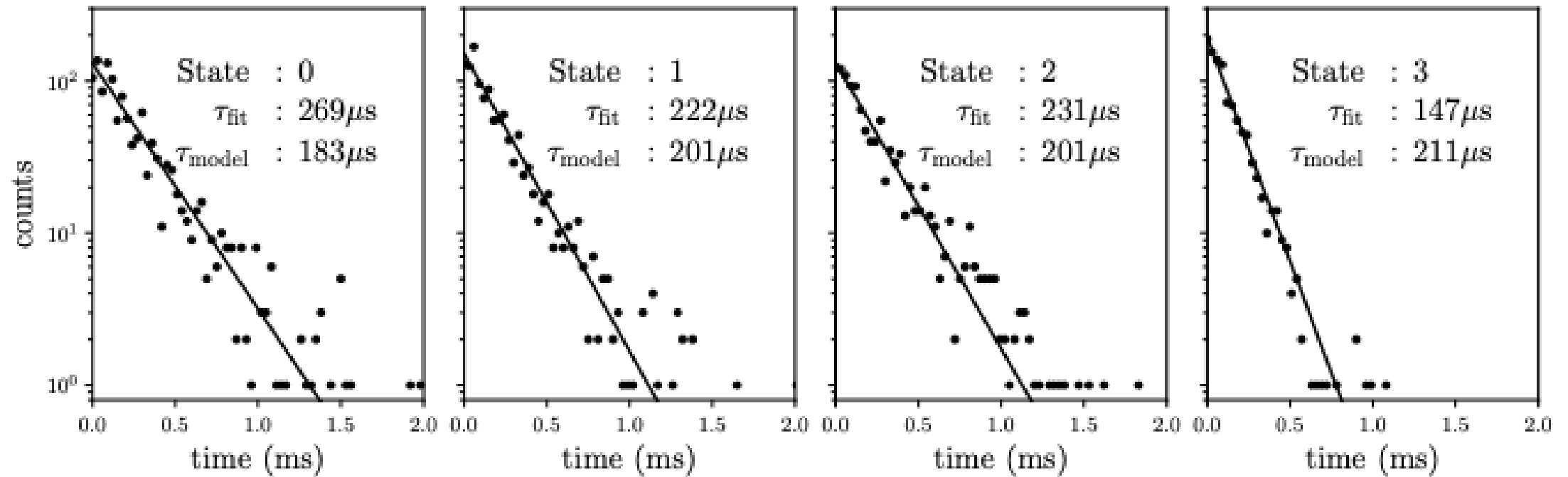


[D. T. Le, C. Müller, R. Navarathna, A. Fedorov, and T. M. Stace, Operating a passive on-chip superconducting circulator: Device control and quasiparticle effects, Phys. Rev. Res. 3, 043211 \(2021\).](#)

Full fits of fig.2



HMM fitting



Nonreciprocity and fidelity

$$\mathcal{N} = \|\mathbf{S} - \mathbf{S}^T\|/\sqrt{8},$$

$$\mathcal{F} = 1 - \sum_{i,j} ||S_{ij}| - |S_{ij}^{\text{ideal}}||/8,$$

ideal circulator : $\mathcal{N}=\sqrt{3/4}$, $\mathcal{F}=1$

$$S^{\text{ideal}} = \begin{pmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{pmatrix} \text{ or } \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{pmatrix}$$