Designing a Josephson ring circuit for a passive on-chip microwave circulator

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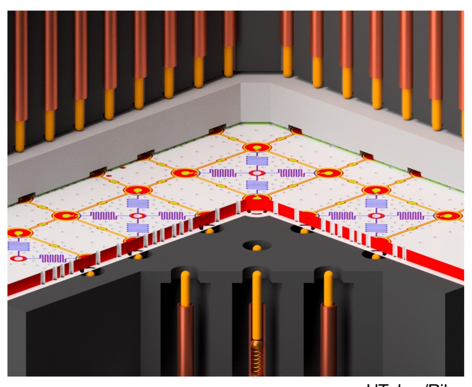
Abstract

Microwave circulators are one of the essential components to build a quantum computing system using superconducting qubits. As conventional circulators are bulky and potentially set a limit of a scale of the system, on-chip circulators not relying on ferrites are intensively studied these days. We investigate a passive Josephson ring circulator proposed by J. Koch *et al.* in 2010 towards its experimental implementation. Here we discuss two issues on experimental difficulties of Josephson ring circulators: uniformity of circuit parameters and impedance matching. The original scheme does not have enough tuning knobs for impedance matching under a finite deviation of circuit parameters. We propose a modified circuit configuration to solve this difficulty towards experimental realization of on-chip circulators.

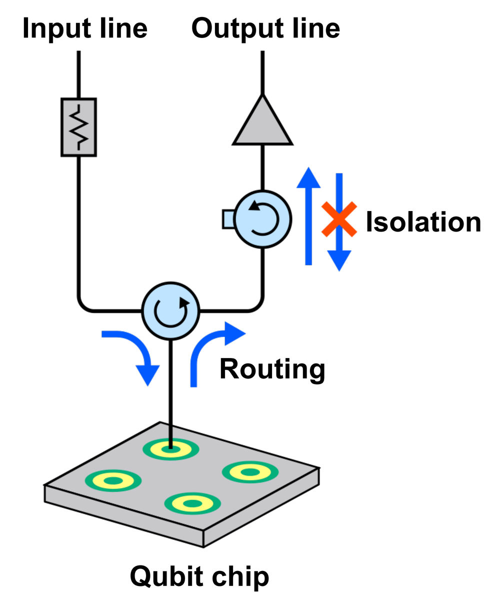
Introduction

Circulators in superconducting quantum computers

Superconducting qubits are expected to be a platform for large-scale quantum computers running on quantum error correcting codes. To realize fault-tolerant quantum computers, it is necessary to scale up the number of qubits to ~10^6 while maintaining high fidelities of qubit control and readout. In a typical readout circuit of a superconducting qubit, circulators are used to route the readout signal and to isolate the qubit from the noise from a amplifier chain.



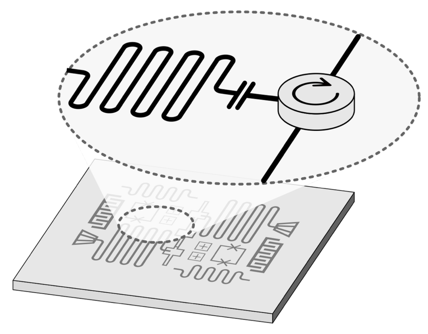
Number of qubits $10^2 \rightarrow 10^6$



Since the ferrite circulators commonly used are bulky and have a large stray magnetic field, they could be a limitation for scaling up superconducting quantum computers. The goal of this research is to develop an on-chip circulator as an alternative to ferrite circulators.

Issues in terms of scalability

- Large size
- Fabrication compatibility
- High magnetic field



Previous Studies

On-chip circulators using superconducting circuits

- Common fabrication process with qubits
- Lower magnetic field operation

Active circuit

Break time-reversal symmetry (TRS) by external AC drive

Demonstrations

- Frequency conversion + delay
  B. Chapman *et al. PRX* **7**, 041043 (2017)
- Parametric coupling
  F. Lecocq *et al. PRApplied* **7**, 024028 (2017)

Issues in terms of scalability

- Many coaxial lines
- Complex parameter tuning

Passive circuit

Break TRS by inherit properties of a superconducting circuit (No external AC drive)

Theoretical proposals (not realized yet)

- Aharonov-Bohm effect
  J. Koch *et al. PRA* **82**, 043811 (2010)
- Aharonov-Casher effect
  C. Müller *et al. PRL* **120**, 213602 (2018)

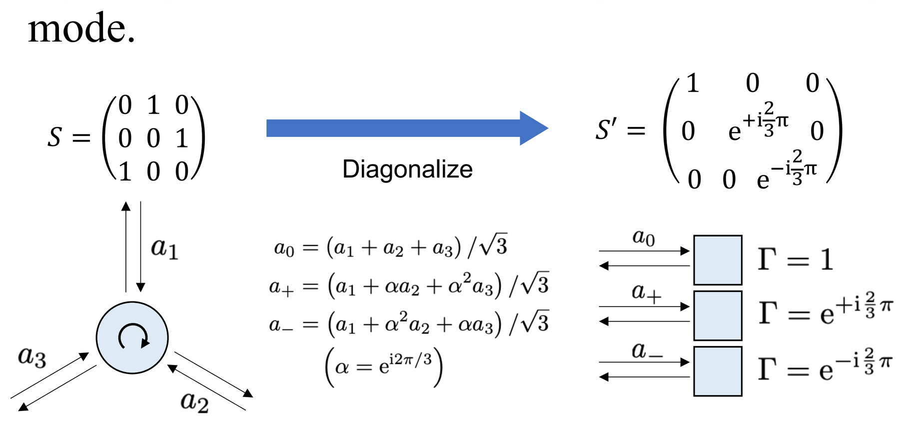
Experimental difficulties

- Sensitive to charge noise
- Lack of tuning knobs ← solve this problem

Principle

Implementation of 3-port circulator

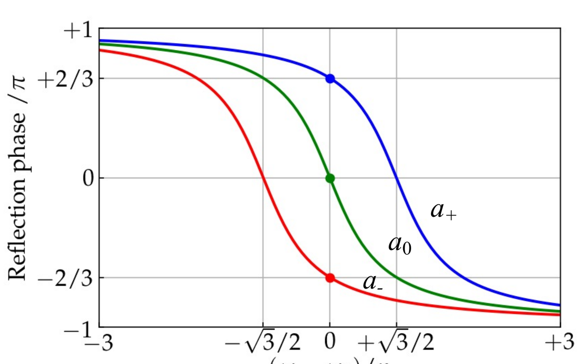
The circulator is a non-reciprocal element which transmits incoming signal to next port, such as 1→2, 2→3 and 3→1. By diagonalizing the S-matrix for a circulator, this behavior turns out to be equivalent to reflecting all 3-phase signals perfectly with 0-, ±2π/3-phase shifts respectively for the input 3-phase mode.



$$S = \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{pmatrix} \quad S' = \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{+i\frac{2}{3}\pi} & 0 \\ 0 & 0 & e^{-i\frac{2}{3}\pi} \end{pmatrix}$$

$$a_0 = (a_1 + a_2 + a_3)/\sqrt{3}$$
$$a_+ = (a_1 + \alpha a_2 + \alpha^2 a_3)/\sqrt{3}$$
$$a_- = (a_1 + \alpha^2 a_2 + \alpha a_3)/\sqrt{3}$$
$$(\alpha = e^{i2\pi/3})$$

$$a_0: \Gamma = 1, \quad a_+: \Gamma = e^{+i\frac{2}{3}\pi}, \quad a_-: \Gamma = e^{-i\frac{2}{3}\pi}$$

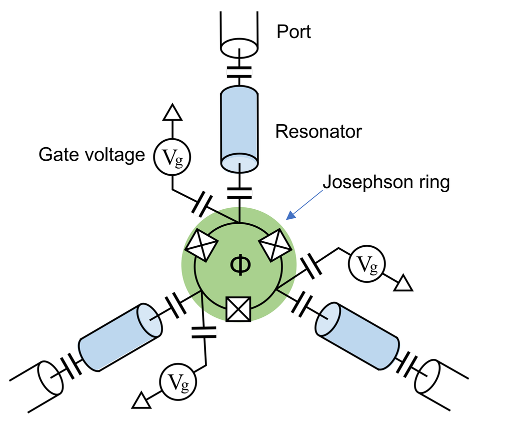


Reflection phase of the resonators which have different eigenfrequencies for different 3-phase excitations, respectively

Josephson ring circulator

J. Koch *et al. PRA* **82**, 043811 (2010)

J. Koch *et al.* have shown that effective couplings between three resonators mediated by a Josephson ring circuit can take complex values and are tunable with external flux. As a special case, the coupled resonators with external ports behave as a circulator when two conditions are satisfied.



Josephson Ring Circulator

Circulator conditions for effective couplings

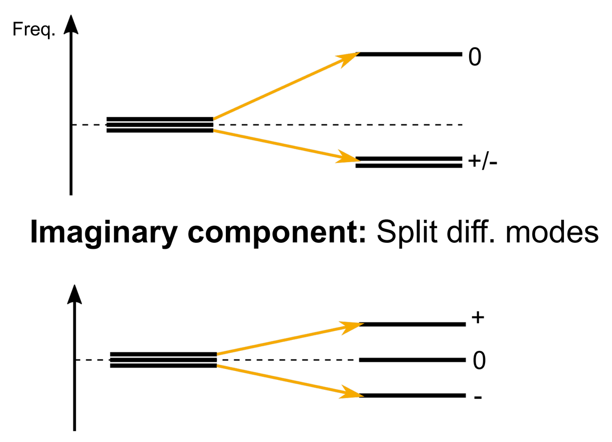
1. Real component is zero
2. Imaginary component is matched to the external linewidth: impedance matching

Problem: lack of tuning knobs

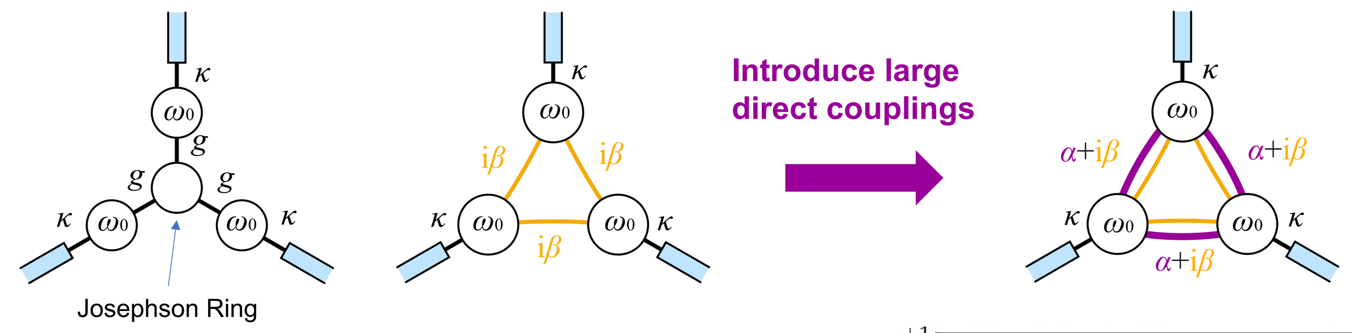
Proposal

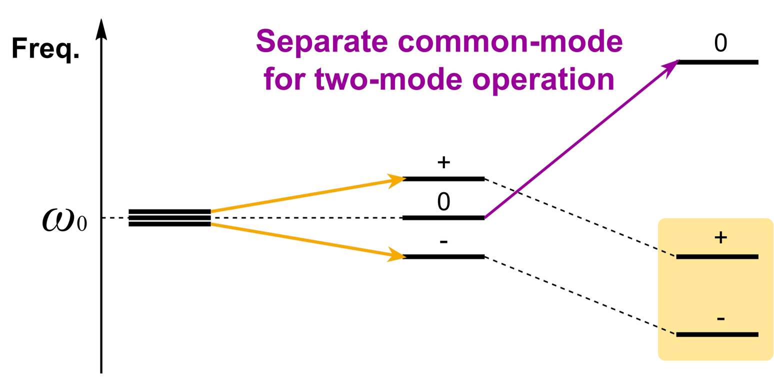
Two-mode operation of Josephson ring circulator

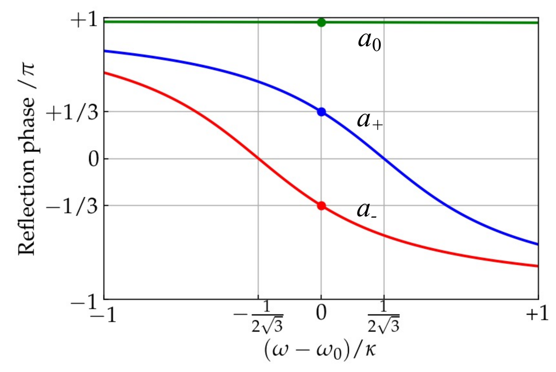
We propose a new operating regime of Josephson ring circulators by adding sufficiently large real-valued couplings between resonators intentionally. This modification relaxes the required conditions, and the impedance mismatch caused by a Josephson enery randomness in real devices can be compensated by a single tuning knob.



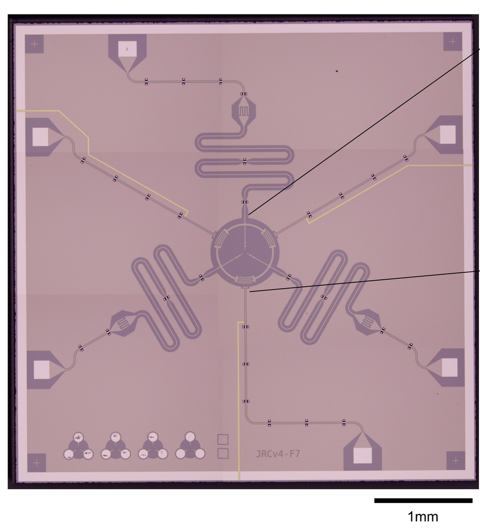
Effect of complex coupling between resonators

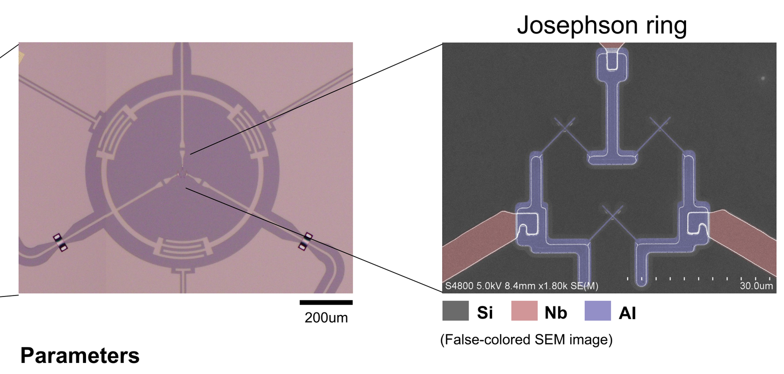






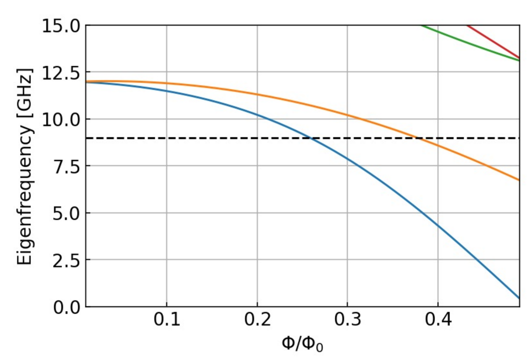
Device Design



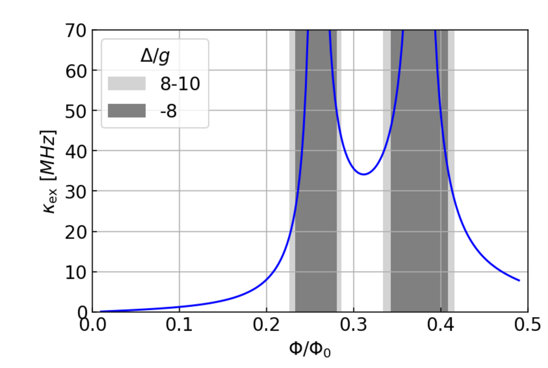


Parameters

Resonators	Frequency	8.9 GHz
	External linewidth	38, 50, 63 MHz
Josephson ring	Charging energy Ec/h	1.24 GHz
	Josephson energy EJ/h	7-9 GHz
	EJ/Ec	5.6-7.3
Coupling	Resonator-Josephson ring	70 MHz
	Resonator-Resonator	430 MHz



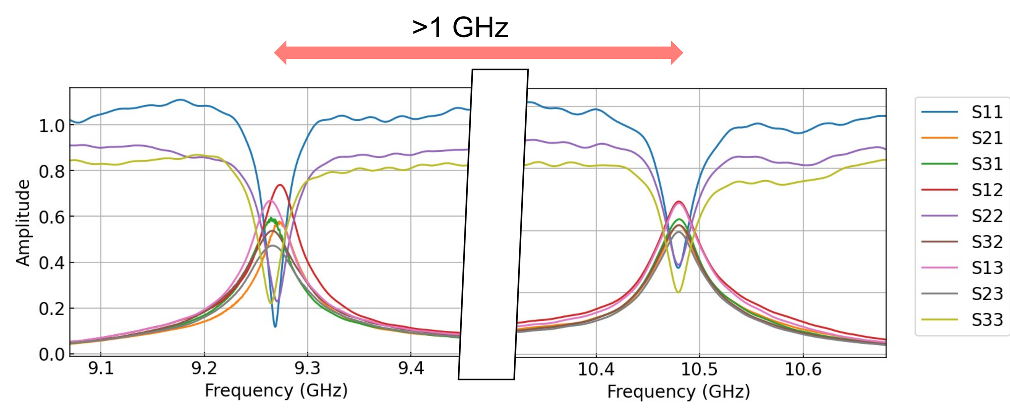
Flux bias vs eigenfrequency of Josephson ring

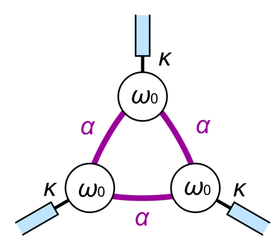


Flux bias vs external coupling for impedance matching

Frequency separation of common mode

We measured the reflection and transmission spectra at 10 mK with a sufficiently high probe power where the Josephson ring was saturated and imaginary couplings vanished. We confirmed frequency separation of the common mode was achieved while maintaining sufficient three-fold symmetry.





Future works

- Improve uniformity of Josephson junctions
- Suppress charge noise

Conclusion

Objective

Realization of a passive on-chip circulator to replace ferrite circulators in superconducting qubit readout circuits

Proposal

New operating regime of Josephson ring circulators overcoming one of the experimental difficulties: lack of tuning knobs problem

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