Microwave single-photon detectors

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Photodetectors for light

Avalanche photodiode

Superconducting nanowire detector

Microwave vs optical photons

\[ E_{\text{MW}} = \hbar \omega_{\text{MW}} \]

\[ E_{\text{opt}} = \hbar \omega_{\text{opt}} \]

\[ \frac{E_{\text{opt}}}{E_{\text{MW}}} = \left( \frac{1.5 \, \mu\text{m}}{3 \, \text{cm}} \right)^{-1} = 20,000 \]
Microwave quantum optics in superconducting circuit QED systems

- Cavity QED and waveguide QED
- Impedance-matched Λ-system
- Λ-system in driven Jaynes-Cummings model
- Perfect absorption and single photon detection
- Qubit-photon entangling gate
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Superconducting qubit – nonlinear resonator

**LC resonator**

**Josephson junction resonator**

Josephson junction = nonlinear inductor

anharmonicity \( \Rightarrow \) effective two-level system

inductive energy = confinement potential
charging energy = kinetic energy \( \Rightarrow \) quantized states
From vacuum to qubit
From vacuum to qubit
From vacuum to qubit
From vacuum to qubit
From vacuum to qubit
From vacuum to qubit
Atom and artificial atom

LC resonator

Superconducting qubit
= artificial atom
~mm

Atom
~ Å
Circuit QED

“Cavity”  “Atom”

Coupling

Light  Matter
Waveguide QED in superconducting circuits
Resonant scattering in 3D space

- Small scattering cross section
- Spatial mode mismatch between incident and radiated waves
Destructive interference of transmitted wave
⇒ Extinction of transmittance
⇒ Perfect reflection
Atom-photon strong coupling

Strong coupling in cavity QED

\[ g \gg \kappa, \gamma, \gamma_\varphi \]

“Strong coupling” in 1D waveguide

\[ \Gamma_1 \gg \gamma, \gamma_\varphi \]
Waveguide QED systems in optics

Atom and nanofiber

Quantum dot and photonic-crystal waveguide


Artificial atom in 1D waveguide

I.-C. Hoi et al. PRL 107, 073601 (2011) Chalmers
A.F. van Loo et al. Science 342, 1494 (2013) ETH Zurich
Transmission spectroscopy — elastic scattering

>99% with transmon
PRL 110, 263601 (2013)

\[ \Gamma_{1D}/\Gamma' \sim 100 \]

Perfect reflection
Power dependence — saturation of atom

\[ r = -r_0 \frac{1 + i\delta\omega / \Gamma_2}{1 + (\delta\omega / \Gamma_2)^2 + \Omega_R^2 / \Gamma_1 \Gamma_2} \]

\[ r_0 = \frac{\Gamma_1}{2\Gamma_2} = \frac{\Gamma_1}{\Gamma_1 + 2\Gamma_\varphi} \]

\[ \Gamma_1 / 2\pi = 11.0 \text{ MHz} \]
\[ \Gamma_\varphi / 2\pi = 1.7 \text{ MHz} \]
\[ M = 12.2 \text{ pH} \]

Inherent nonlinearity of the two-level atom
Resonance fluorescence: inelastic scattering

Dressed state

Pump

\( \omega_0 \)

\( \Omega_R \)

\( \Omega_R \)

\( \Omega_R \)

Fluorescence

Mollow triplet

\( S (10^{-24} \text{ W/Hz}) \)

\( \delta \omega/2\pi (\text{MHz}) \)

\( P_{in} (\text{dBm}) \)

Flux qubit as a three-level artificial atom

- effective two-level system
- auxiliary states
- large anharmonicity/nonlinearity
- selection rule
Spectroscopy of a three-level atom

\[ \frac{\delta \Phi}{\Phi_0} \times 10^{-3} \]

\[ \frac{\omega_{01}}{2\pi} (\text{GHz}) \]

\[ \pi \]

\[ \suppressed \ excitation \ due \ to \ selection \ rule \]
Ladder system at degeneracy point: induced transparency

\[ |2\rangle \quad \Omega_R \quad |1\rangle \quad |0\rangle \]

pump \rightarrow \text{ladder-type}

probe \rightarrow

"Electromagnetically-induced transparency"

\[ \Gamma_{10} < \Gamma_{21} < \Omega_R \]

increasing pump power

\[ \propto \chi'' \]

\[ \propto \chi' \]

\[ \text{Re}(t) \]

\[ \text{Im}(t) \]

\[ \delta \omega_{01}/2\pi \text{ (MHz)} \]
Ladder system at degeneracy point: induced transparency

\[ |0\rangle \quad |1\rangle \quad |2\rangle \]

\[ \Omega_R \]

pump

| 0 \rangle \quad | 1 \rangle \quad | 2 \rangle \]

\[ \Omega_R \]

dressed state

Autler-Townes doublet

Transmission of probe signal

A. A. Abdumalikov et al. PRL 104, 193601 (2010)
Stimulated emission and amplification

\[ |0\rangle \rightarrow |1\rangle \rightarrow |2\rangle \]

\[ \Omega_R \]

pump \[ \rightarrow \] relaxation \[ \rightarrow \] population inversion

\[ |1\rangle \rightarrow |0\rangle \]

stimulated emission

amplification

O. Astafiev et al. PRL 104, 183603 (2010)
Impedance-matched $\Lambda$ system in dressed states
Impedance-matched \( \Lambda \)-type three-level system

1D waveguide

- Down-conversion
- Single photon detector
- Single photon memory

\( \tau_p \gg 1/\Gamma_{10} \)

\( \omega_{01} \)

Raman transition with 100% efficiency

**Deterministic**
- Down convertor
- Single photon detector
- Single photon memory

**Perfect reflection**

**Perfect absorption**
(impedance matching)
Deterministic photon-photon gate using a passive atomic node

atom-photon SWAP, $\sqrt{\text{SWAP}}$

• Bad cavity regime OK \[ \kappa \gg g \quad \Gamma = 4g^2/\kappa \]
• No need of atomic state control/initialization/measurement

K. Koshino, S. Ishizaka, YN, PRA 82, 010301(R) (2010)
Λ system in driven Jaynes-Cummings model

Rotating frame at $\omega_d$

Artificial $\Lambda$-type atom

Impedance matching

CPW resonator + Flux qubit

Qubit drive

$P_d$, $\omega_d$

$\delta \omega_d = \omega_{ge} - \omega_d < 2\chi$

Flux qubit capacitively coupled to a resonator

\[
\begin{align*}
\kappa / 2\pi &= 16.4 \text{ MHz} & Q &= 650 \\
\omega_r / 2\pi &= 10.678 \text{ GHz} & g / 2\pi &= 230 \text{ MHz} \\
\omega_{ge} / 2\pi &= 5.461 \text{ GHz} & 2\chi / 2\pi &= 40 \text{ MHz} & \gamma / 2\pi &= 1 \text{ MHz}
\end{align*}
\]

Strongly dispersive regime: \( g > \chi > \kappa, \gamma \)
Spectroscopy of dressed states – perfect absorption

K. Inomata et al. PRL 113, 063604 (2014)
Microwave single-photon detector
Experimental setup

\[ \frac{\chi}{2} \text{ resonator + flux qubit} \]

\[ \text{Drive} \]

\[ \text{Pump} \quad 2\omega_0 \quad P_{pm} > P_{th} \]

Parametric phase-locked oscillator

\( (\chi/4 \text{ resonator + SQUID}) \)

Signal

IN

Circulators

\[ \omega_0 \]

OUT

Readout signal
Detection of itinerant microwave photon

**Pulse Sequence**

*Initial state*  
$|g, 1\rangle$  
$|e, 1\rangle$  
$|g, 0\rangle$  
$|e, 0\rangle$

*Λ state*  
$|\tilde{4}\rangle$  
$|\tilde{3}\rangle$  
$|\tilde{1}\rangle$  
$|\tilde{2}\rangle$

*Readout state*  

$\delta \omega_d / 2\pi = 49 \text{ MHz}$

**Drive**

- Photon pulse
- Readout pulse

**Signal**

- $\omega_{41}$
- $\bar{n} \sim 0.1$

**Pump**

- $2\omega_r$
Single-photon detection

Drive

Photon pulse

Signal

Pump

\[ \Delta t_d = 178 \text{ ns} \]

\[ \bar{n}_p = \bar{n} \sim 0.12 \]

Maximum Efficiency: \(0.66 \pm 0.06\)

Theory

K. Inomata et al.
Nature Commun. 7, 12303 (2016)
Reset procedure

Initial state

\[ |g, 1\rangle \quad |e, 1\rangle \quad |g, 0\rangle \quad |e, 0\rangle \]

\[ \Lambda \text{ state} \]

\[ |4\rangle \quad |3\rangle \quad |1\rangle \quad |2\rangle \]

\[ \text{Readout state} \]

\[ \Delta t_{\text{dr}} = 380 \text{ ns} \]

\[ \Delta t_{\text{rst}} = 250 \text{ ns} \]

\[ \bar{n} \approx 43 \]

\[ P(|1\rangle) = 0.017 \pm 0.002 \]
Continuous-mode operation


Single-photon detection with impedance-matched Λ system

Real-time dispersive qubit readout
Quantum nondemolition (QND) detection of an itinerant microwave photon

Unpublished data will be posted on arXiv soon. Sorry that it is omitted here.
QND measurement of optical photons

Atom and Optical cavity
A. Reiserer et al., Science 342, 1350 (2013)

detection efficiency 74%
survival probability 66%
Dark count probability 2.9%
Cavity QED

Superconducting qubit (Artificial atom)

Josephson junction

Al 3D cavity

Dipole-dipole interaction

Effective TLS

\[ U \]

\[ |e\rangle \]

\[ |g\rangle \]
Qubit-cavity interaction

Jaynes-Cummings Hamiltonian

\[ H_{JC} = \frac{\hbar \omega_q}{2} \hat{\sigma}_z + \hbar \omega_c \hat{a}^\dagger \hat{a} + \hbar g (\hat{\sigma}_+ \hat{a} + \hat{\sigma}_- \hat{a}^\dagger) \]

for \( g \ll \Delta \equiv \omega_c - \omega_q \quad \chi \equiv g^2 / \Delta \)

\[ H = \frac{\hbar \omega_q}{2} \hat{\sigma}_z + \hbar \omega_c \hat{a}^\dagger \hat{a} - \hbar \chi \hat{a}^\dagger \hat{a} \hat{\sigma}_z \]

Dispersive interaction

Qubit-cavity interaction for the Jaynes-Cummings Hamiltonian with states \( |0\rangle \), \( |1\rangle \), \( |2\rangle \), \( |g\rangle \), and \( |e\rangle \)
Photon number distribution in itinerant mode

\begin{equation*}
\frac{(\omega_d - \omega_q)}{2\pi} \text{ (MHz)}
\end{equation*}

Qubit drive frequency

\begin{equation*}
P_n(n) = 0.22
\end{equation*}

\begin{equation*}
P_n(n) = 0.04
\end{equation*}

\begin{equation*}
\alpha = 0.49
\end{equation*}

\begin{equation*}
r = 0.54
\end{equation*}

\begin{equation*}
\eta = 0.58
\end{equation*}

S. Kono et al. PRL 119, 023602 (2017)
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