# Theory of deterministic switching of a superconducting qubit induced by individual microwave single photons

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## 1. Interaction between photon and impedance-matched Λ system

In one-dimensional optical setups (waveguide QED systems), the interaction between atoms and waveguide photons is drastically enhanced due to the spatial mode matching and the resultant destructive interference between input photons and radiation from the atoms. In particular, when a waveguide photon is reflected by a Λ-type three-level system, the input photon may deterministically induce the Raman transition in the Λ system and switch its electronic state. The necessary conditions are (i) the two decay rates from the top level of the Λ system are identical (impedance-matched Λ system) and (ii) the input photon is in resonance with the Λ system and has a long coherence length [1]. In this work, we implemented such an impedance-matched Λ system by the dressed-state engineering of a dispersively coupled qubit-resonator system [2]. We performed microwave spectroscopy of this Λ system by using a weak continuous microwave as a probe. We confirmed that, after reflection, the input wave loses its amplitude completely (~25dB attenuation) and is down-converted with high efficiency (~75%). These results imply the nearly deterministic excitation of a superconducting qubit induced by individual microwave photons. This deterministic quantum dynamics is applicable to the single photon detection in the microwave domain [3] and to the quantum-state exchange (SWAP gate) between a photon qubit and a superconducting qubit [2].

## 2. Implementation of impedance-matched Λ system

In our device, a driven flux qubit is dispersively coupled to a resonator, which is capacitively connected to a semi-infinite waveguide (waveguide 1) [Fig. (a)] [4,5]. We use the four lowest levels of the qubit-resonator system ($|g,0\rangle$, $|e,0\rangle$, $|g,1\rangle$, $|e,1\rangle$) in this work. Due to the dispersive shift, the level structure of the four levels becomes nested in the rotating frame at a proper drive frequency [Fig. (b)]. The drive field mixes the lower (higher) two states $|g,0\rangle$ and $|e,0\rangle$ ($|g,1\rangle$ and $|e,1\rangle$) to form the dressed states $|1\rangle$ and $|2\rangle$ ($|3\rangle$ and $|4\rangle$). We label the dressed states from the lowest and denote the $|i\rangle\to|j\rangle$ radiative decay rate by $\kappa_{ij}$ (i=3,4 and j=1,2) [Fig. (c)]. At this drive frequency, the radiative decay rates become sensitive to the drive power and the condition $\kappa_{31}=\kappa_{32}$ or $\kappa_{41}=\kappa_{42}$ can be satisfied at a certain drive power [Fig. (d)]. Then we use $|1\rangle$, $|2\rangle$ and $|i\rangle$ (i=3 or 4) as an impedance-matched Λ system.

## 3. Microwave spectroscopy

We applied a weak continuous microwave from waveguide 1 as a probe and measured its reflection coefficient by using a vector network analyzer. We observed the impedance matching, i.e., complete extinction of the reflection field amplitude, when the drive power is chosen to satisfy $\kappa_{31}=\kappa_{32}$ ($\kappa_{41}=\kappa_{42}$) and the probe is tuned to the $|1\rangle\leftrightarrow|3\rangle$ ($|1\rangle\leftrightarrow|4\rangle$) transition. However, the expected and observed drive power deviate slightly. This is due to the use of a rather strong probe and the resultant saturation of the $\Lambda$ system (population of $|2\rangle$), which is inevitable in actual measurements in order to improve the SN ratio.

After reflection, the input field undergoes nearly complete frequency down-conversion. We amplified the reflected field by a Josephson parametric amplifier and measured its power spectrum. The spectrum has two peaks that originate from the down-converted signal wave and its idler. The central frequency of the down-converted signal is lower than the input frequency by 64 MHz. By extracting the signal component in the power spectrum and integrating it, we estimated the conversion efficiency to be 75.0±10.0%, where the uncertainty comes from the inaccuracy in the estimation of the total gain in the output microwave lines. The loss of the efficiency is due to the saturation, which can be improved by using a weaker field or single photons as the input.

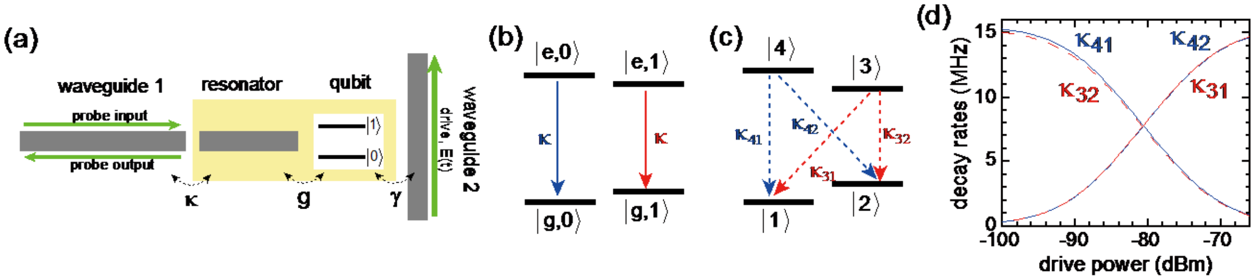

Figure : (a) Schematic of the device. A flux qubit is coupled to a resonator and then to waveguide 1. We apply a probe field from waveguide 1 and a qubit drive field from waveguide 2. (b) Level structure of the qubit-resonator system in the rotating frame. Under a proper choice of the drive frequency, the level structure becomes nested. (c) Level structure of dressed states. Due to the mixing by the drive, the radiative decay may occur in two directions. (d) Radiative decay rates between dressed states as functions of the drive power. At a certain power, the two decay rates from the excited states become identical, i.e., $\kappa_{31}=\kappa_{32}$ or $\kappa_{41}=\kappa_{42}$.

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