Efficient Tunable Microwave Single-photon Source Based on Transmon Qubit

Yu Zhou*‡, Zhihui Peng†, Yuta Horiuchi‡, O. V. Astafiev§¶‖** and J. S. Tsai‡*
*Center for Emergent Matter Science
RIKEN, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan
†Key Laboratory of Low-Dimensional Quantum Structures and Quantum Control of Ministry of Education
Department of Physics and Synergetic Innovation Center for Quantum Effects and Applications
Hunan Normal University, Changsha 410081, China
‡Department of Physics
Tokyo University of Science, 1-3 Kagurazaka, Shinjuku-ku, Tokyo 162-8601,Japan
§Department of Physics
Royal Holloway, University of London, Egham, Surrey TW20 OEX, UK
¶National Physical Laboratory, Teddington TW11 OLW, UK
‖Skolkovo Institute of Science and Technology, Moscow 143026, Russia
**Moscow Institute of Physics and Technology, Dolgoprudny 141700, Russia

***Abstract*—Single-photon sources of high efficiency are of great interest because they are the key elements in many prospective quantum technologies and applications. Based on our previous work, here we demonstrate a high-quality tunable microwave single-photon source based on transmon qubit with intrinsic emission efficiency more than 99%. To further confirm the single-photon property of the source, we study the single-photon interference in a Hanbury-Brown-Twiss (HBT) type setup and measure the correlation functions of the emission field using linear detectors with GPU-enhanced signal processing technique. The antibunching in second-order correlation function is clearly observed. The theoretical calculations agree well with the experimental results. Such a high-quality single-photon source may be used as a building block for quantum communication, simulation and information processing in microwave regime.**

***Index Terms*—superconducting qubit, microwave single-photon, tunable**

I. Introduction

Generating single photon is important not only for fundamental interest in quantum mechanics but also for practical applications in quantum communication, sensing, simulation and computing. Single-photon source thus has been extensively studied in optics and great progress has been made [1]. While single photon source using superconducting circuits [2] has also attracted great interest because of the unique property of superconducting quantum system which can easily achieve strong light and matter interaction, therefore allowing to reach high efficiency in generating and detecting microwave photons. There have already been some implementations of single-photon source which are based on cavity QED system [3]–[6]. Instead of confining the photons with fixed cavity mode, recently several single photon sources have also been demonstrated by strong coupling to one-dimensional (1D) continuum [7] and generating tunable single photons, using either flux qubit [8] or transmon qubit [9]–[11].

Here we demonstrate a high-quality tunable on-demand microwave single-photon source based on transmon qubit with intrinsic emission efficiency above 99% and a systematic study of single photon source demonstrates correlation function measurement with GPU-enhanced signal processing technique. The theoretical numerical calculations agree well with the experimental results.

II. Device and experiment setup

Our single-photon source, see Fig. 1, consists of a transmon capacitively coupling to two 1D coplanar-waveguide transmission line, one is weakly coupled for control (c) and the other is strongly coupled for emission (e).

The sample showed in Fig. 1 is fabricated using standard fabrication technique for superconducting circuits. The transmission line is made of Nb film on an undoped sillicon wafer. The transmon consisting of a dc-SQUID is fabricated with standard Al/AlOx/Al shadow evaporation technique using an electron beam evaporation system.

Here we use the linear detectors to carry out the correlation function measurement [4], [12]. Instead of FPGA, we use CPU with GPU-enhanced signal processing technique to calculate correlation functions.

III. Spectrum and Emission Efficiency

Firstly we characterize our single photon source by measuring the transmission from control line to emission line using a vector network analyzer. As shown in Fig. 2(a), the single-photon source can be tuned from 4 GHz to 7 GHz. There are two avoided-crossings observed due to the coupling to two-level-system (TLS) defects.

Then we characterize the emission efficiency $\eta = \Gamma_1^e/\Gamma_1$ by measuring the reflection at emission line, where $\Gamma_1^{e/c}$ is the relaxation rate through the emission/control line and $\Gamma_1 = \Gamma_1^c + \Gamma_1^e + \Gamma_1^n$ is the total relaxation rate, including non-radiative

978-1-7281-1196-4/19/$31.00 ©2019 IEEE

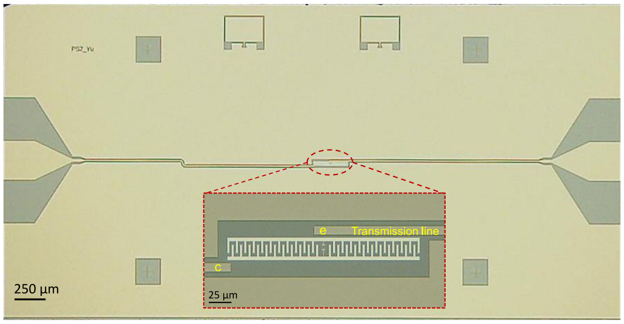

Fig. 1. Optical image of the sample and inset shows the magnified structure of the single-photon source with a transmon.

relaxation rate Γ_1^n. As described in Ref. [8], [13], the photon emission amplitude is related to the annihilation operator $\langle \sigma^- \rangle$ and we can get the reflection at emission r_e as

$$r_e = 1 - \frac{\Gamma_1^e}{\Gamma_2} \cdot \frac{1 - i\delta\omega/\Gamma_2}{1 + (\delta\omega/\Gamma_2)^2 + \Omega^2/(\Gamma_1\Gamma_2)} \ , \qquad (1)$$

where $\delta\omega = \omega_d - \omega_{01}$ is the detuning between drive frequency ω_d and transition frequency ω_{01}, Ω is the rabi frequency and $\Gamma_2 = \Gamma_1/2 + \gamma$ is the dephasing rate which includes pure dephasing rate γ.

As showed in Fig. 2(b), we measure the reflection r_e at emission line (sweet-point) with probe power from weak driving at -146 dBm to strong driving at -126 dBm. The data is normalized to its background when transmon is tuned far away from the sweet-point. Fitting the data using Eq. (1), we can get $\eta = \Gamma_1^e/\Gamma_1 \geq \Gamma_1^e/(2\Gamma_2) = 0.992 \pm 0.001$. Note here, the high emission efficiency indicates that the emitted photons will almost all come out through the emission line and the pure dephasing γ is also very small.

Furthermore, we also estimate the emission efficiency over a wide frequency range, as shown in Fig. 2(c). Apart from TLS defects, we can achieve emission efficiency $\geq 90\%$ over 1 GHz frequency range.

IV. Correlation Function Measurement

Furthermore, we measure the correlation functions of the emitted photons using linear detectors [12] with HBT setup.

For calculation of correlation functions, we follow the same way as in Ref. [4], [12]:

$$\Gamma^{(1)}(\tau) = \int \langle S_a^*(t) S_b(t+\tau) \rangle dt \ , \qquad (2)$$

$$\Gamma^{(2)}(\tau) = \int \langle S_a^*(t) S_a^*(t+\tau) S_b(t+\tau) S_b(t) \rangle dt \ . \qquad (3)$$

Then we can obtain the correlation function of emitted photons by deducting the traces of noise background, which are measured in the same way as signal traces.

As shown in Fig. 3(c), we see strongly suppressed center peak $G^{(2)}(0) \ll 1$, namely the antibunching, which shows clear evidence of single-photon emission in our source.

V. Conclusion

In conclusion, we have demonstrated a high-quality tunable microwave single photon source based on transmon with intrinsic emission efficiency ~ 0.99. The antibunching in the second-order correlation function is also clearly observed. Such kind of high-quality single-photon source may be used as a building block for quantum communication, simulation and information processing in the microwave regime.

Acknowledgment

This work was supported by CREST, JST. (Grant No. JPMJCR1676), the New Energy and Industrial Technology Development Organization (NEDO), and ImPACT Program of Council for Science, Technology and Innovation (Cabinet Office, Government of Japan). Z.H.P. is supported by NSFC under Grant No. 61833010 and Hunan Province Science and Technology Innovation Platform and Talent Plan (Excellent Talent Award) under grant No.2017XK2021. O.V.A. is supported by Russian Science Foundation (grant N 16-12-00070).

References

[1] P. Senellart, G. Solomon, and A. White, "High-performance semiconductor quantum-dot single-photon sources," *Nature Nanotechnology*, vol. 12, no. 11, pp. 1026–1039, Nov. 2017. [Online]. Available: https://www.nature.com/articles/nnano.2017.218

[2] M. H. Devoret and R. J. Schoelkopf, "Superconducting Circuits for Quantum Information: An Outlook," *Science*, vol. 339, no. 6124, pp. 1169–1174, Mar. 2013. [Online]. Available: http://www.sciencemag.org/cgi/doi/10.1126/science.1231930

[3] A. A. Houck, D. I. Schuster, J. M. Gambetta, J. A. Schreier, B. R. Johnson, J. M. Chow, L. Frunzio, J. Majer, M. H. Devoret, S. M. Girvin, and R. J. Schoelkopf, "Generating single microwave photons in a circuit," *Nature*, vol. 449, no. 7160, pp. 328–331, Sep. 2007. [Online]. Available: http://www.nature.com/doifinder/10.1038/nature06126

[4] D. Bozyigit, C. Lang, L. Steffen, J. M. Fink, C. Eichler, M. Baur, R. Bianchetti, P. J. Leek, S. Filipp, M. P. da Silva, A. Blais, and A. Wallraff, "Antibunching of microwave-frequency photons observed in correlation measurements using linear detectors," *Nature Physics*, vol. 7, no. 2, pp. 154–158, Feb. 2011. [Online]. Available: http://www.nature.com/articles/nphys1845

[5] C. Lang, C. Eichler, L. Steffen, J. M. Fink, M. J. Woolley, A. Blais, and A. Wallraff, "Correlations, indistinguishability and entanglement in Hong–Ou–Mandel experiments at microwave frequencies," *Nature Physics*, vol. 9, no. 6, pp. 345–348, Jun. 2013. [Online]. Available: http://www.nature.com/articles/nphys2612

[6] M. Pechal, L. Huthmacher, C. Eichler, S. Zeytinoglu, A. A. Abdumalikov, S. Berger, A. Wallraff, and S. Filipp, "Microwave-Controlled Generation of Shaped Single Photons in Circuit Quantum Electrodynamics," *Physical Review X*, vol. 4, no. 4, p. 041010, Oct. 2014. [Online]. Available: https://link.aps.org/doi/10.1103/PhysRevX.4.041010

[7] D. Roy, C. M. Wilson, and O. Firstenberg, "Colloquium: Strongly interacting photons in one-dimensional continuum," *Reviews of Modern Physics*, vol. 89, no. 2, p. 021001, May 2017. [Online]. Available: https://link.aps.org/doi/10.1103/RevModPhys.89.021001

[8] Z. H. Peng, S. E. de Graaf, J. S. Tsai, and O. V. Astafiev, "Tuneable on-demand single-photon source in the microwave range," *Nature Communications*, vol. 7, p. 12588, Aug. 2016. [Online]. Available: http://www.nature.com/doifinder/10.1038/ncomms12588

[9] M. Pechal, J.-C. Besse, M. Mondal, M. Oppliger, S. Gasparinetti, and A. Wallraff, "Superconducting Switch for Fast On-Chip Routing of Quantum Microwave Fields," *Physical Review Applied*, vol. 6, no. 2, p. 024009, Aug. 2016. [Online]. Available: https://link.aps.org/doi/10.1103/PhysRevApplied.6.024009

[10] P. Forn-Diaz, C. W. Warren, C. W. S. Chang, A. M. Vadiraj, and C. M. Wilson, "On-Demand Microwave Generator of Shaped Single Photons," *Physical Review Applied*, vol. 8, no. 5, p. 054015, Nov. 2017. [Online]. Available: https://link.aps.org/doi/10.1103/PhysRevApplied.8.054015

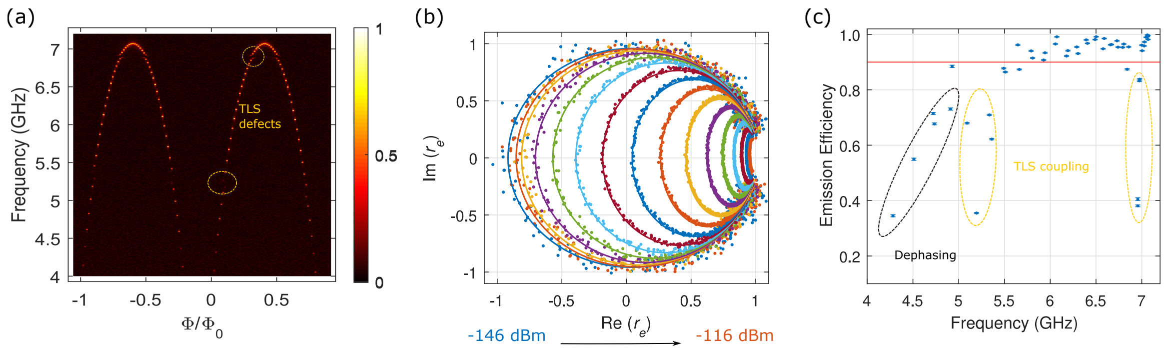

Fig. 2. (a) Normalized transmission spectrum $|t_{ce}/t_{max}|$ vs flux bias. (b) Reflection r_e at emission line when transmon is bias at sweet-point. The experimental data (dots) are normalized to the background when qubit is tuned off-resonance with sweet-point. The probe power range in the plot is from -146 dBm to -126 dBm with 2 dBm/step. The solid lines are the fitting results. (c) Estimated emission efficiency over a wide range. The red line shows the position where efficiency is 90%. The two abnormal drops of emission efficiency in the plot are because of the coupling to TLS defects.

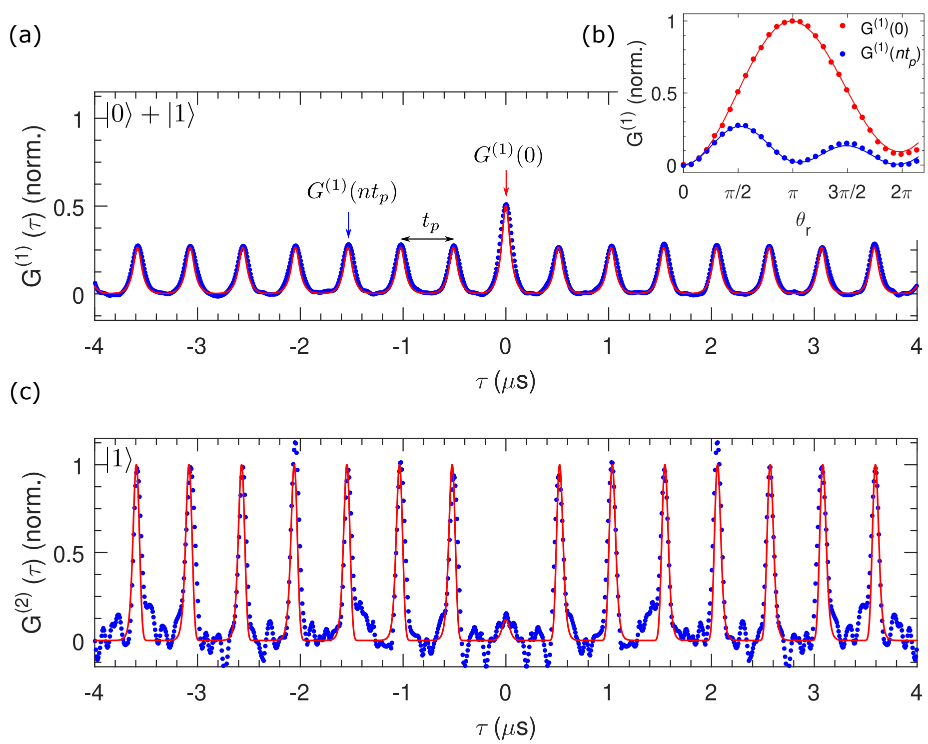

Fig. 3. (a) Time dependence of first-order correlation function $G^{(1)}(\tau)$ for $(|0\rangle + |1\rangle)/\sqrt{2}$. (b) Dependence of center peak $G^{(1)}(0)$ and side-peak $G^{(1)}(nt_p)$ on prepared Rabi angle θ_r. (c) Measured second-order correlation function $G^{(2)}(\tau)$ for state $|1\rangle$. All the dots are experimental data and solid lines are theoretical calculations including the limited detection bandwidth in experiment.

[11] S. Gasparinetti, M. Pechal, J.-C. Besse, M. Mondal, C. Eichler, and A. Wallraff, "Correlations and entanglement of microwave photons emitted in a cascade decay," *Physical Review Letters*, vol. 119, no. 14, p. 140504, Oct. 2017. [Online]. Available: http://arxiv.org/abs/1705.05272

[12] M. P. da Silva, D. Bozyigit, A. Wallraff, and A. Blais, "Schemes for the observation of photon correlation functions in circuit QED with linear detectors," *Physical Review A*, vol. 82, no. 4, p. 043804, Oct. 2010. [Online]. Available: https://link.aps.org/doi/10.1103/PhysRevA.82.043804

[13] O. Astafiev, A. M. Zagoskin, A. A. Abdumalikov, Y. A. Pashkin, T. Yamamoto, K. Inomata, Y. Nakamura, and J. S. Tsai, "Resonance Fluorescence of a Single Artificial Atom," *Science*, vol. 327, no. 5967, pp. 840–843, Feb. 2010. [Online]. Available: http://www.sciencemag.org/cgi/doi/10.1126/science.1181918