Towards highly efficient broadband superconducting quantum memory

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Microwave quantum memory promises advanced capabilities for noisy intermediate-scale superconducting quantum computers. Existing approaches to microwave quantum memory lack complete combination of high efficiency, long storage time, noiselessness and multi-qubit capacity. Here we report an efficient microwave broadband multimode quantum memory. The memory stores two spectral modes of single photon level microwave radiation in on-chip system of eight coplanar superconducting resonators. Single mode storage shows a power efficiency of up to 60 ± 3% at single photon energy and more than 73 ± 3% at high intensity. The demonstrated efficiency is an order of magnitude larger than the previously reported multimode microwave quantum memory. The noiseless character of the storage is confirmed by coherent state quantum process tomography. The demonstrated results pave the way to further increase in efficiency and hence building a practical multimode microwave memory for superconducting quantum circuits.

INTRODUCTION

Fault-tolerant quantum computing and quantum internet require quantum memory as an essential building block of a future quantum information processing platform [1–5]. Superconducting circuits quantum electrodynamics (cQED) is among the leading realizations of intermediate-scale quantum computers [5–7]. Meanwhile there is a strong motivation to break the wall of nearest-neighbor qubit coupling using enhanced cQED architecture with integrated quantum memory [5–6, 8–10]. Moreover, it would allow to extend limited coherence time of the superconducting qubits, implement new quantum algorithms [11] and hardware-efficient quantum error correction [12–15]. Compared with traditional superconducting qubits, high quality factor resonators have a superior potential for quantum state storage due to their impressive lifetime [14–16, 18], efficient thermalization, no extra fridge control lines and ability to couple multiple qubits [8, 19].

Quantum memory based on a single superconducting resonator demonstrates high efficiency in storing a microwave photon with an optimal temporal mode [17–20]. However, the specific exponential rising mode of that memory complicates interconnections with other circuits. The memory stores only a single qubit with a fixed bandwidth that is limited by a coupling with an input waveguide. To increase bandwidth of a memory and its multi-qubit capacity, it is promising to use multi-resonator schemes [8, 21–22], which can overcome the restrictions of a single resonator.

The first approach uses a linear chain of coupled resonators [8]. Interaction between resonators leads to an emergence of collective modes with different frequencies and different coupling constants between the resonators and closely spaced qubits. Each of the collective modes can be used to selectively store the quantum state of a particular qubit by tuning the qubit’s frequency into resonance with that mode. However, this scheme provides efficient storage only for specific temporal waveform as in single-resonator quantum memory.

The second multi-resonator approach [22] exploits the ideas of photon/spin echo [23,24] in a system of resonators with a linear periodic spacing of their resonant frequencies. An echo forms in such resonators and reemits an input pulse after \( \tau = 1/\Delta \), where \( \Delta \) is the frequency spacing between resonators. In this case, the effective bandwidth of the memory is determined by the span of the formed frequency comb, which significantly exceeds the linewidth of an individual resonator. This idea was used for on-demand storage of two temporal modes with an efficiency of 6% [25].

Here, we demonstrate a broadband two mode on-chip microwave quantum memory with storage efficiency of 60 ± 3% at single photon energy. First, we portray our design and show storage results of coherent pulses for two modes with independent carrier frequencies. Next, we present a complete quantum characterization of the storage for a single mode at small photon numbers by quantum process tomography. Finally, the obtained results and future perspectives of unity efficiency, on-demand and long-lived storage for the realized quantum memory are discussed.

RESULTS

Our quantum memory device (Fig. 1a) consists of one common resonator that interacts with eight internal superconducting resonators and coupling waveguide as it is depicted at principal scheme in Fig. 1b. The common resonator has a designed frequency of 6 GHz with length...
FIG. 1: (a) Image of the fabricated quantum memory device. The color area around the internal $\lambda/4$ resonators is a vortex-pinning hole array that helps achieve high internal Q-factor by magnetic vortices trapping [30]. Inset: optical micrograph of the quantum memory chip. “IN” indicates the input port that is connected to the common resonator with a voltage tap. (b) Principal scheme of the quantum memory device with the relative positions of the common resonator (green line), first group internal resonators (blue line), second group of internal resonators (red line) and input port (brown line). (c) Simplified scheme of the experimental setup: arbitrary waveform generator (AWG), analog-to-digital converter (ADC), continuous-wave local oscillator (LO), chain of attenuators (ATN), quantum-limited Josephson parametric amplifier (JPA), two low-noise amplifiers based on high-electron-mobility transistor (HEMT), phase shifter (PS). The colors indicate the different temperature stages for the components. (d) Simulated stationary reflection spectrum $S_{11}$ for the first (blue solid line) and the second (red solid line) quantum memories and the frequency-shifted single common resonator (green solid line). The carrier frequencies for first and second memory cells are indicated as dashed blue and red vertical lines, respectively.

of $8\cdot\lambda/4$, where $\lambda$ is the resonant wavelength. The waveguide is coupled to the common resonator with a coupling constant $\kappa \approx 281$ MHz.

Each of the eight internal resonators has length of $\sim \lambda/4$ and is coupled to the common resonator with coupling constant $g \approx 12$ MHz. The internal resonators have unloaded Q-factor $\sim 5 \cdot 10^5$ that corresponds to decay constant $\gamma_n \approx 6$ kHz that is same as decay constant for common resonator $\gamma_0 \approx 6$ kHz. The proper choice of $g$, $\kappa$ and $\gamma_n$ is crucial for impedance matching condition [22] (see supplementary materials for a theoretical model), that assures the efficient transfer of an input pulse from the waveguide into the internal resonators. The designed frequencies of the internal resonators range from 5.9895 GHz to 6.0105 GHz with a step of $\Delta = 3$ MHz. We keep the position of each internal resonator in the voltage antinodes of the common resonator as it is shown in Fig. 1b. Such positioning allows to choose
an identical coupling constant for all internal resonators since coupling depends only on a mutual capacitance that can be fabricated with good precision. In turn, the position $l_{\text{short}}$ of the input port relatively to the common resonator is crucial for the value of coupling constant $\kappa$ as we show in supplementary materials.

We adopt a small difference in $\Delta$ of 0.5 MHz for two groups of resonators labeled as 1-4 and 5-8 in Fig. 1 to select two frequency modes for storage and separate them in time domain. We measure the resonators 1 to 4 to be frequency spaced by $\Delta_{1-4} = 3.55$ MHz, while resonators 5 to 8 are spaced by $\Delta_{5-8} = 3.08$ MHz. Hence we consider these two groups of resonators as two independent quantum memory cells, namely first and second, for two modes with carrier frequencies 5.9436 GHz and 5.9549 GHz, respectively.

Simplified scheme of the experimental setup for characterizing quantum memory is depicted in Fig. 5 (see supplementary materials for experimental setup details). The quantum memory is installed in a dilution refrigerator at the base stage with temperature of 10 mK together with microwave circulators and a quantum-limited Josephson parametric amplifier. An intermediate frequency (up to 500 MHz) signal from an arbitrary waveform generator is mixed with a radio frequency signal from the continuous wave local oscillator on an IQ mixer. The mixing result is used to prepare pulses with fixed amplitude, phase and carrier frequency shifted relative to the local oscillator frequency by an intermediate frequency. The pulses are then attenuated by the total -80 dB attenuation that prepares the pulses in a coherent state and ensures the noise temperature is close to the base stage temperature of 10 mK [31]. According to this attenuation value the total signal power in single photon regime is $\sim150$ dBm. The circulator directs the prepared coherent state of microwave radiation into the quantum memory chip. The reflected signal from the memory is routed by the circulator into a quantum-limited Josephson parametric amplifier and two low-noise amplifiers. These two amplifiers are based on high-electron-mobility transistor (HEMT) and placed at temperature of 4K and room temperature, respectively. Hence the memory’s output is totally amplified by $\sim90$ dB that brings noise of it’s quantum fluctuation 20 dB above noise level of the analog-to-digital converter. The amplified signal is mixed on the IQ mixer with the local oscillator that is phased locked to an input signal and phase-tuned to measure arbitrary quadrature. The resulted quadratures in I and Q channels are sampled by fast analog-to-digital converters for further analysis.

First we present experimental results on storage efficiency for intensive coherent microwave pulses. For each group of resonators, we perform independent experiments by tuning the carrier frequency of the input pulse to the central frequency of each group of the resonators, as shown in Fig. 1c. The input pulse has a Gaussian waveform with full width at half maximum of 115 ns that matches the bandwidth of each memory cell. The pulses are measured by heterodyne detection with local oscillator being detuned by 50 MHz.

An amplitude of the resulted beating signal in time domain is compared to the one of reference pulse with the same amplitude, but being sent out of resonance with the quantum memory. The reference pulse is detuned from the resonances of both quantum memories. However, the intensity of the reference pulse depends on the choice of the detuning as HEMT amplifier’s gain varies over frequency. We determine the average value of pulse intensity at 21 frequencies in the range from 5.8 GHz to 5.9 GHz. The measurements show that the variance of the reflected signal intensity is 10.7%. This value is used to determine an accuracy of calculating the efficiency of the quantum memory.

In Fig. 2a we present normalized time-domain data at the outputs of both memories for a input pulse at high power with large average photon number ($n_{\text{ph}} \gg 1$). The first memory cell with resonators 1-4 irradiates 75 ± 8% of the input power in the first echo after 277 ns, while the second memory cell (5-8) outputs 52 ± 5.7% of input power in its first echo after 310 ns. At the same time, the reflected power with no delay is larger for the second memory cell. We attribute this difference in efficiencies to the impedance matching condition being better fulfilled in the first memory cell than in the second one due to common resonator frequency shift. Fig. 2b shows theoretically simulated reflection spectrum of the both memory cells with respect to the common resonator. Here in the regime of the detuned common resonator the effective coupling monotonically decreases for the internal resonators closer to the frequency of the common resonator. Overall, it leads to a smaller efficiency of the second memory cell in an absence of multi-resonator impedance matching. For both memory cells, the total integrated power over 1.5 $\mu$s was $\sim96\%$ of the input energy. The acquired experimental data for both memories is fitted to our theoretical model with a good agreement.

Next we perform experiments on a storage of microwave pulses at a single photon level in the first quantum memory cell. We gradually decrease the intensity of the signal pulse and observe a reduction in the efficiency of the echo from 75 ± 8% to 58 ± 6.4% in single photon regime. The inset of Fig. 2a shows a dependence of the efficiency on the intensity of the input signal pulse. It is an expected effect that is associated with the presence of saturable two-level system (TLS) defects in the superconducting resonators [32–34]. We model this effect by increasing the decay rate to $\gamma_n = 165$ kHz in single photon regime, thus effectively reducing Q-factor to 36 × 10^3. Fig. 2b shows time domain data on amplitude of the echo averaged over a series of experiments with single photon level coherent pulses. This data is in good agreement with the theoretical model, where the change
FIG. 2: (a) The signals from the first (red solid line) and second (green solid line) memory cells at high power with large average photon number. (b) The signals from the first memory cell (red solid line) at single photon level input pulse intensities. The signals are normalized to the maximum intensity of the input Gaussian-shaped coherent pulse (blue solid line). The black dashed and dotted lines are theoretical simulations with parameters discussed in the text. Efficiency dependence for input pulse intensity is shown in the inset. (c) Four pairs of experimentally acquired phase space distribution for input pulses ('IN') and the corresponding memory’s response ('OUT'). Single color and arrow indicate a single pair of phase space distributions of conjugate position \(X\) and momentum \(P\) for state of the mode being sent into the memory and recalled state. (d) Diagonal elements of the reconstructed quantum process tensor.

in the decay constants of the resonator modes is taken into account.

We confirm a noiseless character of our quantum memory by performing coherent state quantum process tomography on our memory with a single microwave mode \(|\alpha\rangle\). We specify the quantum memory’s operation as a process tensor \(E_{nm}^{jk}\) that linearly relates input \(\rho^{in}\) to output \(\rho^{out}\) density matrices of the microwave mode in Fock basis:

\[
\rho^{out}_{jk} = \sum_{m,n=0}^{H} E_{nm}^{jk} \rho^{in}_{nm},
\]

where \(H\) is high-energy cut-off that truncates the Fock space of interest. If the process is phase invariant with respect to phase of an input coherent state, then only diagonal elements of the process tensor are non-trivial.

First, we demonstrate that our quantum memory is phase invariant by consequently storing coherent states \(|\alpha\rangle = |\alpha e^{i\phi}\rangle\) with the same amplitude \(|\alpha| \sim 9\) but with different phases. The input and echo pulses in Gaussian temporal mode are measured by homodyne detection (see supplementary materials for details about the measurement and calibration). Based on these measurements, we reconstruct phase-space distributions of quadratures for input and echo pulses. The memory shows a constant phase shift of \(\sim \pi/4\) radians for co-
herent states with different phases as it is depicted in Fig. 2c. The same phase-invariant behaviour is observed at lower amplitudes (|α| ∼ 1).

Next, we reconstruct the process tensor by the maximum-likelihood method [33]. We fix a phase of the input pulse and vary its amplitude from 0 to 1.2 with a step of 0.02. For each amplitude’s value we perform multiple experiments and acquire 2 · 10^5 quadratures. The sampled distribution of recorded quadratures is used to reconstruct the process tensor in the Fock space of dimension 4, as it is depicted in Fig. 2d. The presented diagonal elements \( \mathcal{E}_{nm}^{nn} \) correspond to probabilities of detecting n-th Fock state at the output of the quantum memory for m-th Fock state being sent as an input.

The memory proves to be noiseless with a probability of getting a noisy photon less than 1%. From the reconstructed process tensor, the single photon power efficiency is estimated to be 60 ± 3% that is consistent with heterodyne measurements at low intensity. The non-linear trend of power efficiency is presented with 73 ± 3% being a reconstructed efficiency for |2⟩ and |3⟩ Fock states. As the single pulse is stored in the group of 4 resonator we expect that the observed saturation of the TLS at low intensity may be attributed to the relatively long life-time of the TLS compare to the period of the tomographic experiment (∼50 μs). This effect will be a subject of a separate study.

**DISCUSSION**

The demonstrated efficiencies of 60% for single photons and 75% for higher intensities in the single quantum memory cell can be increased if the condition of impedance matching is exactly met. Our theoretical model predicts efficiency of 73% for single photons and more than 96% for multi-photon states under complete impedance matching with the efficiency being limited only by the coherence time of the internal resonators. Moreover, further technological improvements in term of TLS mitigation with novel superconductive material platforms like niobium and tantalum [39,40] can significantly reduce the losses in the internal resonators and increase efficiency even closer to unity in single photon regime with a lifetime close to a millisecond.

It is worth noting that the demonstrated quantum memory suppresses coupling of the quantum noise from the internal resonator into output waveguide according to our model. We show in supplementary material that the suppression factors for \( \gamma_0 = \gamma_n = 165 \text{ kHz} \) and 6 kHz are ∼0.14 and 0.006, respectively. It means that the quantum memory can operate at temperatures higher than 10 mK. For example, single photon storage with a signal-to-noise ratio of ∼100 can be achieved at temperatures of 100 mK and 600 mK for \( \gamma_0 = \gamma_n = 165 \text{ kHz} \) and 6 kHz, respectively.

The demonstrated quantum memory stores a signal pulse for a fixed time interval. However, the scheme can be modified for on-demand storage, if a fast switch [20] is used to connect and disconnect the quantum memory from the input waveguide. In this way, the storage time of signal pulses is a multiple of \( n/\Delta \), where \( n \) is an arbitrary integer that is set by the switch. Recently, it was shown that only one switch is enough to achieve on-demand storage while keeping high efficiency and low noise at optimal parameters in such multi-resonator memory [41]. In comparison with single resonator memories [17,20], the switch may operate when only the internal resonators are excited with the common resonator being empty that avoids corruption of the stored data from the switch’s noise. The switch induced losses in the common resonator would not significantly effect the performance of the quantum memory as we show in supplementary material.

The realized quantum memory operates with two frequency multiplexed modes. However, the memory design with identical \( \Delta \) would be able to store multiple temporal qubits. This multi-qubit memory in conjunction with a quantum router would allow to implement quantum random access memory [12,14], where the role of the router can be realized by superconducting circuits with Josephson junctions.

In conclusion, we presented noiseless two-mode on-chip quantum memory for microwave photons that is compatible with superconducting cQED architecture. The obtained experimental results agree well with the theory, which predicts a further considerable increase of efficiency towards 100%. It will open an avenue for a practical multi-qubit memory with arbitrary temporal and spectral mode multiplexing with a range of applications in superconducting quantum processing.

**DATA AVAILABILITY**

The data that support the findings of this study are available from the corresponding author upon reasonable request.

**ACKNOWLEDGMENTS**

Device was fabricated at the BMSTU Nanofabrication Facility (Functional Micro/Nanosystems, FMNS REC, ID 74300). The work of S.A.M., K.I.G and E.S.M. were carried out with financial support of the Ministry of Education and Science of Russia, Reg. number NIOKRT 121020400113-1. Authors thank Tatiana G. Konstantinova for assistance in manufacturing of the quantum memory chip and Vladimir V. Echeistov for the help in configuring the room temperature electronics. S.A.M. acknowledges N.S. Perminov for useful discussions, E.S.M.
thanks A. Tashchilina for helpful discussions.

**AUTHOR CONTRIBUTIONS**

S.A.M., K.I.G. and I.A.R. proposed the experiment. A.R.M., N.S.S., V.I.P and K.I.G. performed the main parameters calculation and designed scheme. The technology was developed by E.V.Z., N.S.S. and I.A.R. E.S.M. proposed the quantum process tomography experiment. A.R.M., E.I.M and A.I.I configured the experimental setup and carried out the measurements. A.A.S. and A.R.M., E.I.M and A.I.I configured the experimental parameters calculation and designed scheme. The technology was developed by S.A.M., K.I.G. and E.S.M.. S.A.M and E.S.M. performed numerical simulation and analysed the experimental data. The theory was developed by S.A.M., K.I.G. and E.S.M. S.A.M and E.S.M wrote the manuscript with an assistance of all authors. I.A.R and S.A.M supervised the project.

**COMPETING INTERESTS**

The authors declare no competing interests.

**ADDITIONAL INFORMATION**

Suplementary information accompanies this paper at http://www.nature.com/naturecommunications.

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[1] H. J. Kimble, Nature **453**, 1023 (2008)
[2] A. I. Lvovsky, B. C. Sanders, and W. Tittel, Nat Photon **3**, 706 (2009)
[3] S. Wehner, D. Elkouss, and R. Hanson, Science **362**, eaam9288 (2018)
[4] A. Blais, A. L. Grimsmo, S. M. Girvin, and A. Wallraff, Rev. Mod. Phys. **93**, 025005 (2021)
[5] M. Mariantoni, H. Wang, T. Yamamoto, M. Neeley, R. C. Bialczak, Y. Chen, M. Lenander, E. Lucero, A. D. O’Connell, D. Sank, M. Weides, J. Wenner, Y. Yin, J. Zhao, A. N. Korotkov, A. N. Cleland, and J. M. Martinis, Science **334**, 61 (2011)
[6] M. Kjaergaard, M. E. Schwartz, J. Braumüller, P. Krantz, J. I.-J. Wang, S. Gustavsson, and W. D. Oliver, Annual Review of Condensed Matter Physics **11**, 369 (2020)
[7] M. H. Devoret and R. J. Schoelkopf, Science **339**, 1169 (2013)
[8] R. K. Naik, N. Leung, S. Chakram, P. Groszkowski, Y. Lu, N. Earnest, D. C. McKay, J. Koch, and D. I. Schuster, Nature Communications **8**, 1904 (2017)
[9] W. Pfaff, C. J. Axline, L. D. Burkhart, U. Völ, P. Reinhold, L. Frunzio, L. Jiang, M. H. Devoret, and R. J. Schoelkopf, Nature Physics **13**, 882 (2017)
[10] C. J. Axline, L. D. Burkhart, W. Pfaff, M. Zhang, K. Chou, P. Campagne-Ibarcq, P. Reinhold, L. Frunzio, S. Girvin, L. Jiang, et al., Nature Physics **14**, 705 (2018)
[11] V. Giovannetti, S. Lloyd, and L. Maccone, Phys. Rev. Lett. **100**, 230502 (2008)
[12] Z. Leghtas, G. Kirchmair, B. Vlastakis, R. J. Schoelkopf, M. H. Devoret, and M. Mirrahimi, Physical Review Letters **111**, 120501 (2013)
[13] A. D. Corcoles, E. Magesan, S. J. Srinivasan, A. W. Cross, M. Steffen, J. M. Gambetta, and J. M. Chow, Nature communications **6**, 1 (2015)
[14] N. Ofek, A. Petrenko, R. Heeres, P. Reinhold, Z. Leghtas, B. Vlastakis, Y. Liu, L. Frunzio, S. Girvin, L. Jiang, et al., Nature **536**, 441 (2016)
[15] S. Rosenblum, P. Reinhold, M. Mirrahimi, L. Jiang, L. Frunzio, and R. J. Schoelkopf, Science **361**, 266 (2018)
[16] M. Reagor, W. Pfaff, C. Axline, R. W. Heeres, N. Ofek, K. Slawa, E. Holland, C. Wang, J. Blumoff, K. Chou, M. J. Hatridge, L. Frunzio, M. H. Devoret, L. Jiang, and R. J. Schoelkopf, Phys. Rev. B **94**, 014506 (2016)
[17] J. Wenner, Y. Yin, Y. Chen, R. Barends, B. Chiaro, E. Jeffrey, J. Kelly, A. Megrant, Y. M. Mutus, C. Neill, P. J. J. O’Malley, P. Roushan, D. Sank, A. Vainsencher, T. C. White, A. N. Korotkov, A. N. Cleland, and J. M. Martinis, Phys. Rev. Lett. **112**, 210501 (2014)
[18] O. B. Kobe, J. Chuma, R. J. Jr., and M. Chose, Engineering Science and Technology, an International Journal **20**, 460 (2017)
[19] Y. Kubo, C. Grezes, A. Dewes, T. Umeda, J. Isoya, H. Sumiya, N. Morishita, H. Abe, S. Onoda, T. Ohshima, et al., Physical review letters **107**, 220501 (2011)
[20] E. Flurin, N. Roch, J. D. Pillet, F. Mallet, and B. Huard, Phys. Rev. Lett. **114**, 090503 (2015)
[21] D. C. McKay, R. Naik, P. Reinhold, L. S. Bishop, and D. I. Schuster, Phys. Rev. Lett. **114**, 080501 (2015)
[22] S. A. Moiseev, K. I. Gerasimov, R. R. Latypov, N. S. Perminov, K. V. Petrovink, and O. N. Shersyukov, Scientific Reports **8**, 3982 (2018)
[23] S. A. Moiseev and S. Kröll, Phys. Rev. Lett. **87**, 173601 (2001)
[24] H. de Riedmatten, M. Afzelius, M. U. Staudt, C. Simon, and N. Gisin, Nature **456**, 773 (2008)
[25] W. Tittel, M. Afzelius, T. Chanelière, R. Cone, S. Kröll, S. Moiseev, and M. Sellars, Laser & Photonics Reviews **4**, 244 (2010)
[26] C. Grezes, B. Julsgaard, Y. Kubo, W. L. Ma, M. Stern, A. Béland, K. Nakamura, J. Isoya, S. Onoda, T. Ohshima, V. Jacques, D. Vion, D. Esteve, R. B. Liu, K. Mölmer, and P. Bertet, Phys. Rev. A **92**, 020301 (2015)
[27] V. Ranjan, J. O’Sullivan, E. Albertinale, B. Albanese, T. Chanelière, T. Schenkel, D. Vion, D. Esteve, E. Flurin, J. J. L. Morton, and P. Bertet, Phys. Rev. Lett. **125**, 210505 (2020)
[28] E. S. Moiseev, A. Tashchilina, S. A. Moiseev, and B. C. Sanders, New Journal of Physics **23**, 063071 (2021)
[29] Z. Bao, Z. Wang, Y. Wu, Y. Li, C. Ma, Y. Song, Y. Lu, N. Earnest, D. C. McKay, J. Koch, and D. I. Schuster, Nature Communications **8**, 173601 (2017)
[30] M. H. Devoret and R. J. Schoelkopf, Science **339**, 1169 (2013)
[31] W. Pfaff, C. J. Axline, L. D. Burkhart, U. Völ, P. Reinhold, L. Frunzio, L. Jiang, M. H. Devoret, and R. J. Schoelkopf, Nature Physics **13**, 882 (2017)
[32] J. Gao, M. Daal, J. M. Martinis, A. Vayonakis, J. Zmuidzinas, B. Sadoulet, B. A. Mazin, P. K. Day, and H. G. Leduc. Appl. Phys. Lett. 92, 212504 (2008). arXiv:0804.0467

[33] J. D. Brehm, A. Bilmes, G. Weiss, A. V. Ustinov, and J. Lisenfeld. Appl. Phys. Lett. 111, 112601 (2017). arXiv:1709.00381

[34] M. Kudra, J. Biznárová, A. Fadavi Roudsari, J. J. Burnett, D. Niepce, S. Gasparinetti, B. Wickman, and P. Delsing. Appl. Phys. Lett. 117, 070601 (2020)

[35] M. Lobino, D. Korystov, C. Kupchak, E. Figueroa, B. C. Sanders, and A. I. Lvovsky. Science 322, 563 (2008). https://www.science.org/doi/pdf/10.1126/science.1162086

[36] M. Lobino, C. Kupchak, E. Figueroa, and A. I. Lvovsky. Phys. Rev. Lett. 102, 203601 (2009)

[37] S. Rahimi-Keshari, A. Scherer, A. Mann, A. T. Rezakhani, A. I. Lvovsky, and B. C. Sanders. New Journal of Physics 13, 013006 (2011).

[38] A. Anis and A. I. Lvovsky. New Journal of Physics 14, 105021 (2012)

[39] A. P. M. Place, L. V. H. Rodgers, P. Mundada, B. M. Smitham, M. Fitzpatrick, Z. Leng, A. Premkumar, J. Bryon, A. Vrajitoarea, S. Sussman, G. Cheng, T. Madhavan, H. K. Babla, X. H. Le, Y. Gang, B. J., A. Gyenis, N. Yao, R. J. Cava, N. P. de Leon, and A. A. Houck. Nature Communications 12, 1779 (2021)

[40] C. Wang, X. Li, H. Xu, Z. Li, J. Wang, Z. Yang, Z. Mi, X. Liang, T. Su, C. Yang, G. Wang, W. Wang, Y. Li, M. Chen, C. Li, K. Linglu, J. Han, Y. Zhang, Y. Feng, Y. Song, T. Ma, J. Zhang, R. Wang, P. Zhao, W. Liu, G. Xue, Y. Jin, and H. Yu. npj Quantum Information 8, 3 (2022)

[41] S. A. Moiseev and N. S. Perminov. JETP Letters 111, 500 (2020)

[42] V. Giovannetti, S. Lloyd, and L. Maccone. Phys. Rev. Lett. 100, 160501 (2008)

[43] E. S. Moiseev and S. A. Moiseev. Journal of Modern Optics 63, 2081 (2016)

[44] K. C. Chen, W. Dai, C. Errando-Herranz, S. Lloyd, and D. Englund. PRX Quantum 2, 030319 (2021)