

Slow and stored light via electromagnetically induced transparency using a Λ -type superconducting artificial atom

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(Received 7 March 2024; revised 26 July 2024; accepted 22 November 2024; published 21 January 2025)

Recent progresses in Josephson-junction-based superconducting circuits have propelled quantum information processing forward. However, the lack of a metastable state in most superconducting artificial atoms hinders the development of photonic quantum memory in this platform. Here we use a single superconducting qubit-resonator system to realize a desired Λ -type artificial atom, and to demonstrate slow light with a group velocity of 3.6 km/s and the microwave storage with a memory time extending to several hundred nanoseconds via electromagnetically induced transparency. Our results highlight the potential of achieving microwave quantum memory, promising substantial advancements in quantum information processing within superconducting circuits.

DOI: [10.1103/PhysRevResearch.7.L012015](https://doi.org/10.1103/PhysRevResearch.7.L012015)

Optical quantum memory is a fundamental and crucial ingredient in a quantum network [1] that can store and retrieve the photonic information on demand. Moreover, it serves as the building block in buffering, synchronizing, and distributing entanglements across various nodes and locations within the network [2–4].

In the microwave regime, superconducting circuits have become the prospective platform for quantum computing and information processing owing to the engineerable and strong coupling between the circuits and single photons [5–11]. To further build up a quantum network based on superconducting circuits [12], the development of microwave quantum memory is an active topic in the field. Over the past decade, numerous schemes for microwave quantum memory have come to fruition, often relying on the resonator's absorption [13–17] due to long coherence and low dephasing of the resonators [18–20].

For natural atoms, one of the promising approaches to slow and even store the photons in the atomic media is based on electromagnetically induced transparency (EIT) [21–25]. In EIT media, a weak resonant probe light that strongly interacts with atoms becomes transparent, and its dispersion and group

velocity are precisely controlled by a strong coupling field. By adiabatically controlling the coupling field, the photonic information carried by the probe pulse can be effectively stored in and retrieved from the atomic coherence [26], thus realizing the concept of optical quantum memory [2–4, 27, 28]. Efforts to realize EIT in superconducting circuits have encountered limitations due to the lack of suitable metastable states [29–31]. In the past few years, research progress has been achieved in observing EIT spectroscopy [32–36]. However, two-photon transitions in Refs. [33, 34] cannot be used to store a single photon, and increasing the coupling Rabi frequency disrupts the Λ -type structure in Ref. [35], limiting the storage bandwidth. Consequently, these designs and operating methods are unsuitable for developing EIT quantum memory [37]. The first slow light experiment was based on the dispersion slope due to Autler-Townes splitting instead of EIT in the qubit metamaterial [38]. Investigations into slow and stored light experiments based on EIT in superconducting circuits remain unexplored.

In this Letter we present the experimental realization of EIT slow and stored light phenomena in superconducting waveguide quantum electrodynamics architectures as initially proposed in our recent theoretical investigation [37]. Our approach involves the parametric modulation of the qubit transition frequency, enabling the bridging of the first-order dipole-forbidden sideband transition [39] in a qubit-resonator system [20, 40, 41] and creating an artificial effective Λ -type atom. By employing this parametric modulation technique, which plays the role of the coupling field utilized in real atom scenarios, the phase response of the probe light is

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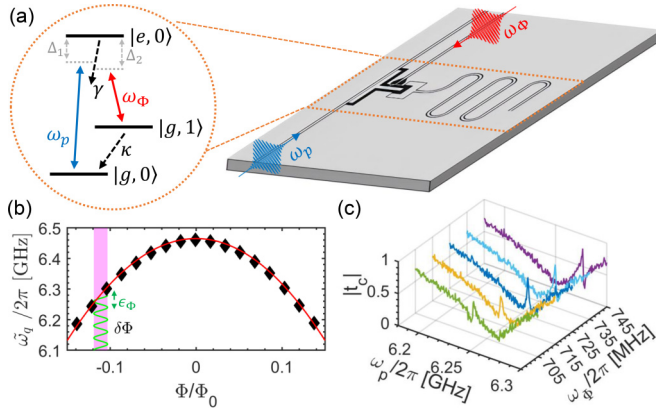


FIG. 1. Λ -type superconducting artificial atom. (a) Schematic of the circuit layout and the corresponding energy-level diagram. The qubit is capacitively coupled to a transmission line and a detuned $\lambda/4$ resonator. The length of the qubit (EIT media) is $L = 340 \mu\text{m}$. The Λ -type energy levels are established with the parametric modulation. (b) $\tilde{\omega}_q$ as a function of the flux Φ (black diamonds). The red solid line denotes the theoretical fit. The green sinusoidal wave indicates the flux modulation $\delta\Phi$, which results in the modulation magnitude of the qubit resonance frequency ϵ_Φ . (c) Two-tone spectroscopy as a function of ω_Φ . A narrow transparent peak within the broad absorption dip is observed with the parametric modulation.

significantly modified and becomes steep. A weak probe pulse is decelerated under the continuous parametric modulation to the qubit, which results in a reduction in its group velocity to 3.6 km/s. Furthermore, by adiabatically switching off and on the parametric modulation, we can partially store and retrieve the pulse, characterized by an average photon count below the single photon level, within the resonator. Our scheme's unique feature, compared to natural atom systems, is the nearly complete compression of a pulse into a single atom instead of distributing it spatially among an ensemble of atoms, demonstrating storage in a distinct regime. This single Λ -type atom EIT offers opportunities to explore fundamental limits in light-matter interactions and single-atom quantum memory [42–44].

Our circuit, illustrated in Fig. 1(a), consists of a tunable superconducting Xmon qubit [45] with the bare transition frequency ω_q strongly coupled to both a one-dimensional open transmission line and a resonator. The corresponding circuit model and the measurement setup are described in the Supplemental Material [46]. The microwave probe signal is injected into the transmission line, where it directly interacts with the qubit. The resonator with the bare resonance frequency ω_r , located at a considerable distance from the transmission line, exhibits a small energy-loss rate κ in comparison to the qubit's total decoherence rate γ . The resonator serves to store microwave photons. The system is operated in the dispersive regime, where the frequency difference between the qubit and the resonator is much larger than their coupling strength $g_{q,r}$ and loss rates. Figure 1(a) shows the energy-level diagram of the Λ -type atom, which comprises the lowest three energy dressed states $|g, 0\rangle$, $|e, 0\rangle$, and $|g, 1\rangle$, where $g(e)$ denotes the qubit is mainly at the ground (excited) state, and the resonator is at the photon Fock state 0 or 1. The probe light directly

drives the transition from the ground state $|g, 0\rangle$ to the excited state $|e, 0\rangle$. Meanwhile, the parametric modulation serves to bridge the otherwise forbidden transition from the excited state $|e, 0\rangle$ to the state $|g, 1\rangle$, where $|g, 1\rangle$ acts as a metastable state due to its longer coherence time compared to $|e, 0\rangle$. As a result, the probe light exhibits transparency through an interference effect induced by the parametric modulation.

Our initial steps involve characterizing the basic properties of the qubit (far detuned from ω_r) by measuring the transmission coefficient t_c of the scattered probe light ω_p with single-tone spectroscopy. The bare qubit transition frequency follows $\omega_q(\Phi) = \sqrt{8E_c E_J(\Phi/\Phi_0)} - E_c$, where E_c denotes the charging energy, $E_J(\Phi/\Phi_0)$ the flux-dependent Josephson energy, Φ the applied magnetic flux, and Φ_0 the flux quantum. The qubit is biased at $\Phi = -0.11\Phi_0$. Via fitting the transmission profile near the dressed qubit transition frequency $\tilde{\omega}_q$, $\tilde{\omega}_q/2\pi = 6.282 \text{ GHz}$, $\Gamma/2\pi = 121 \text{ MHz}$, and $\gamma_\phi/2\pi = 3 \text{ MHz}$ are extracted [30,48,49], where Γ and γ_ϕ are the relaxation rate and the pure dephasing rate of the qubit. For the spectroscopy experiments, $P_p = -141.8 \text{ dBm}$, corresponding to $\Omega_p/2\pi = 7.8 \text{ MHz}$, is fixed. At the same bias, the dressed resonator frequency $\tilde{\omega}_r/2\pi = 5.532 \text{ GHz}$ and its energy loss rate $\kappa/2\pi = 0.78 \text{ MHz}$ are extracted. Such a large κ is mainly caused by the inverse Purcell effect [50]. The bare resonator frequency $\omega_r/2\pi = 5.539 \text{ GHz}$ is observed by a strong probe power $P_p = -96.8 \text{ dBm}$ to saturate the qubit. The coupling $g_{q,r}/2\pi = 73.3 \text{ MHz}$ is determined by analyzing the shift of the resonator [51]. Figure 1(b) depicts how $\tilde{\omega}_q$ varies with Φ , and the best fit gives $E_c/2\pi = 290 \text{ MHz}$, $E_J(\Phi = 0)/2\pi = 19.6 \text{ GHz}$, and the junction asymmetry $d = 0.32$.

To manipulate EIT with our Λ -type atom, we send another coherent light to the flux line to induce the flux modulation, i.e., $\Phi(t) = \Phi + \delta\Phi \sin(\omega_\Phi t)$, where $\delta\Phi$ and ω_Φ are the modulation magnitude and frequency [see Figs. 1(a) and 1(b)]. Modulating the flux Φ results in $E_J(t) = E_J \cos[\pi\Phi(t)/\Phi_0] \sqrt{1 + d^2 \tan^2[\pi\Phi(t)/\Phi_0]}$, and therein the qubit transition frequency is being periodically modulated. In Fig. 1(c) we present $|t_c|$ versus ω_p and ω_Φ . The modulation enables the previously forbidden sideband transition of $|e, 0\rangle$ to $|g, 1\rangle$ with $\omega_\Phi \approx \tilde{\omega}_q - \tilde{\omega}_r$ [37] and leads to a typical Λ -type energy-level diagram with the parametric modulation Rabi frequency Ω_Φ . The magnitude of Ω_Φ is determined by $\Omega_\Phi = 2g_{q,r}J_1(\epsilon_\Phi/2\omega_\Phi)$, where J_1 is the Bessel function of the first kind, and ϵ_Φ is the resulting parametric modulation magnitude of the qubit transition frequency through the flux modulation [37,40]. Under the weak modulation, ϵ_Φ is proportional to $\delta\Phi$, which results in $\Omega_\Phi \propto \delta\Phi$.

Subsequently, we fix $\omega_\Phi/2\pi = 725 \text{ MHz}$ in the experiments. $|t_c|$ as functions of ω_p and $\delta\Phi$ are depicted in Fig. 2(a). Line cuts of Fig. 2(a) and the corresponding phase response are shown in Figs. 2(c) and 2(d). The steady-state response of the probe light in the experiment can be well described via the expectation value $\langle\sigma\rangle$ with the driven Jaynes-Cummings Hamiltonian [see Fig. 2(b)], written as

$$H(t) = \omega_q(t)\sigma^\dagger\sigma + \omega_r a^\dagger a + g_{q,r}(a^\dagger\sigma + \sigma^\dagger a) + \Omega_p \cos(\omega_p t)(\sigma + \sigma^\dagger), \quad (1)$$

where σ ($\sigma^\dagger$) is the lowering (raising) operator for the qubit and a ($a^\dagger$) is the lowering (raising) operator for the resonator.

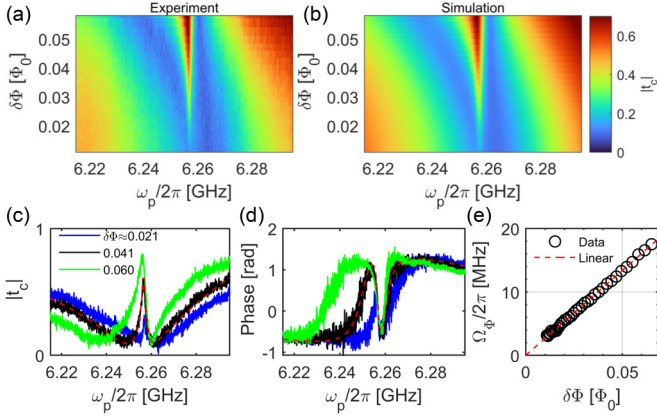


FIG. 2. EIT spectroscopy. (a) False-color spectroscopy of $|t_c|$ of the experiment and (b) the simulation as functions of $\delta\Phi$ and ω_p . (c) Line cuts of the experimental results. (d) The corresponding phase response. The fitting results of the experimental data are depicted in red dashed lines. (e) Ω_ϕ as a function of $\delta\Phi$. Black empty circles are the fitting Ω_ϕ of the data in (a). The red dashed line is the linear fit.

The simulation is done by solving the master equation by using QuTiP [52] and is described in the Supplemental Material [46]. With the parametric modulation, the probe light is no longer reflected by the qubit; instead, it becomes transparent due to the two-photon resonance [21]. As $\delta\Phi$ increases, it leads to the expansion of the EIT window and enhances the transparency of the probe light. Besides, due to the nonlinearity of the qubit transition frequency, there is a frequency shift caused by motional averaging effects [53,54]. Nevertheless, the frequency at which the two-photon resonance occurs remains well within the transparency window, which enables the study of slow and stored light phenomena. In fact, the optimal operating point necessitates biasing at the qubit linear frequency tuning regime, mitigating the qubit frequency shift arising from the parametric modulation [37]. However, $\omega_q(\Phi = 0)$ is not far greater than ω_r in this chip. As a result, the following experimental results are conducted with the qubit biased at $\Phi = -0.11\Phi_0$ to have a trade-off between the inverse Purcell effect and the qubit frequency shifts.

To comprehensively investigate the EIT phenomenon in our setup, we employ analytical modeling with the Λ -type atom interacting with the probe and coupling lights, while considering the frequency shift induced by the parametric modulation on the qubit. Besides, the corresponding frequency shift of the resonator due to the qubit's frequency shift is deemed negligible in our analysis. We define the motional average qubit frequency as $\tilde{\omega}_q^M$. The analytical form for the transmission coefficient is written as [37,55]

$$t_c^a = 1 + i \frac{\frac{\Gamma}{2}(\delta - i\frac{\kappa}{2})}{(\delta - i\frac{\kappa}{2})(\delta + \Delta_2 - i\gamma) - (\frac{\Omega_\phi^2}{4})}, \quad (2)$$

where $\Delta_1 = \tilde{\omega}_q^M - \omega_p$, $\Delta_2 = \tilde{\omega}_q^M - \tilde{\omega}_r - \omega_\phi$, and $\delta = \Delta_1 - \Delta_2$ [see Fig. 1(a)]. The fitting parameters are $\tilde{\omega}_q^M$ and Ω_ϕ . Other parameters are extracted from single-tone spectroscopy. The fitting matches the data shown in Figs. 2(c) and 2(d), verifying that our system behaves as an Λ -type atom. The probe light at a frequency near $\omega_p \approx \tilde{\omega}_q^M \equiv \omega_p^0 = 2\pi \times 6.2565$ GHz

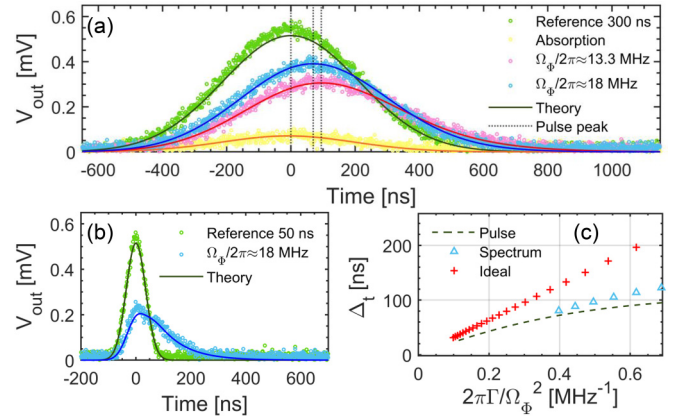


FIG. 3. Demonstration of the slow light. (a) Probe pulse envelopes with different continuous Ω_ϕ . See the text. The pulse with the parametric modulation becomes slower than the reference. The solid lines with different colors are the theoretical predictions of the slow light. The black dotted lines, defined as the pulse peaks, are the times when the maximum amplitudes of the theoretical predictions occur. The corresponding delay times are $\Delta_t = 95$ and 69 ns, respectively. (b) The shorter pulse duration of probe pulse envelopes with continuous Ω_ϕ . (c) Δ_t versus Γ/Ω_ϕ^2 . The dark green dashed line is extracted from the theoretical prediction of the pulse experiments in (a). The light blue empty triangles are analyzed from the spectroscopy data and Eq. (4). The red plus-sign markers are the ideal case, which gives $D = 2$.

becomes transparent. Due to the condition of $\gamma \gg \kappa/2$, the optical response is fully governed by EIT as long as the parametric modulation satisfies the condition $\Omega_\phi < \gamma$. The pulsed experimental data shown later also verify the observation of EIT. Figure 2(e) shows the extracted Ω_ϕ , from the fitting results in Fig. 2(a), as a function of $\delta\Phi$. As expected, Ω_ϕ is linearly increased with $\delta\Phi$.

The rapid change of the phase at the two-photon resonance with the parametric modulation indicates the reduction of the group velocity. In order to investigate the modified group velocity, the delay time of the probe pulse is experimentally measured by transmitting a Gaussian probe pulse through the transmission line. The pulse envelope is expressed as $\Omega_p^s \exp(-t^2/\tau_d^2)$, with $\Omega_p^s/2\pi = 7$ MHz and $\tau_d = 300$ ns. The carrier frequency of the pulse is fixed at $\omega_p^0/2\pi$. The phenomenon of the slow light is depicted in Fig. 3(a). The Gaussian pulse (green empty circles), serving as the reference pulse, is acquired by adjusting the qubit transition frequency away from $\omega_p^0/2\pi$. The pulse (yellow empty circles) represents the interference pattern resulting from the probe pulse and the field emitted by the qubit under a bias of $\Phi = -0.11\Phi_0$. In contrast to the reference pulse, the amplitude of the yellow pulse decreases. The pulses (blue and pink empty circles) are obtained under continuous parametric modulation but $\Omega_\phi/2\pi = 18$ MHz and 13.3 MHz, respectively. Both blue and pink pulses exhibit a delay compared to the reference pulse, indicative of the phenomenon of slow light. Moreover, these pulses manifest transparency effects, in contrast to the case of absorption (yellow pulse), signifying the presence of EIT. The numerical calculations of the slow light with different Ω_ϕ , depicted as the solid lines, match well with the

experimental results. The pulsed delay time Δ_t is defined as the time difference of the maximum amplitude of the theoretical output pulse with the parametric modulation to the center of the reference.

It is known that with the perfect metastable state ($\kappa = 0$), the relation between Δ_t and Ω_Φ in an ensemble of identical atoms is [21]

$$\Delta_t = \frac{D\Gamma}{\Omega_\Phi^2}, \quad (3)$$

where D is the optical depth. We further use Eq. (3) to define the effective D of our single atom. Figure 3(c) depicts Δ_t as a function of Γ/Ω_Φ^2 . Δ_t is also estimated by measuring the derivative of phase θ , obtained from the fittings, at ω_p^0 [see Fig. 2(d)], written as [33,35]

$$\Delta_t = - \left. \frac{d\theta}{d\omega_p} \right|_{\omega_p=\omega_p^0}. \quad (4)$$

The estimations of Δ_t from the results of the pulsed and spectrum experiments are consistent. However, when taking into account the nonzero decoherence rate of the metastable state, the maximum achievable Δ_t becomes limited even if Ω_Φ is weak [21]. Besides, the ideal case of Δ_t in our system, shown as the red plus-sign markers, is obtained via the phase derivation of the two-photon resonance of Eq. (2) by assuming Δ_1 , Δ_2 , and $\kappa = 0$. Comparing the ideal case to Eq. (3), $D = 2$ for a single atom is observed.

Specifically, in the pulsed experiment, the maximum Δ_t is observed to be approximately 95 ns at $\Omega_\Phi/2\pi = 13.3$ MHz. We consider the length of the medium, i.e., the interaction length of the qubit $L = 340$ μm [see Fig. 1(a)], to estimate the group velocity $v_g = L/\Delta_t$. The minimum group velocity of the pulse is reduced to approximately 3.6 km/s. Note that v_g can be further reduced as we decrease Ω_Φ . However, Ω_p should also be reduced to satisfy the EIT condition, i.e., $\Omega_p < \Omega_\Phi$.

For the stored light experiment, we choose a shorter Gaussian probe pulse compared to the previous experiment. The corresponding FWHM of the pulsed spectral bandwidth is larger than the FWHM of the EIT window γ_{EIT} with $D = 2$ [25]. Therefore, the output pulsed shape is distorted, but it allows us to determine the turn-off time of the parametric modulation for the small D . A $\tau_d = 50$ ns Gaussian probe pulse with the maximum $\Omega_\Phi/2\pi = 18$ MHz is used, and its slow light is shown in Fig. 3(b). The spectral FWHM of the probe pulse is about 10.6 MHz, and $\gamma_{\text{EIT}}/2\pi = 1.54$ MHz. The input average photon number of the pulse is $\langle N_p \rangle = 0.08$. Figure 4(a) shows the stored light results. By adiabatically turning off the parametric modulation at the end of the reference probe pulse, a portion of the pulse is stored within the resonator. Subsequently, through adiabatically turning on the parametric modulation after the storage time T_s , the pulse is retrieved back to the transmission line while preserving its original shape. The storage efficiency η , defined as the energy ratio of the retrieved pulse to the reference pulse, is plotted as a function of T_s [see Fig. 4(b)]. The maximum η is up to 5%. The fitting decay rate is about 0.76 MHz, which is close to the coherence of the metastable state κ extracted from the spectroscopy. We highlight that the photon retrieved in our

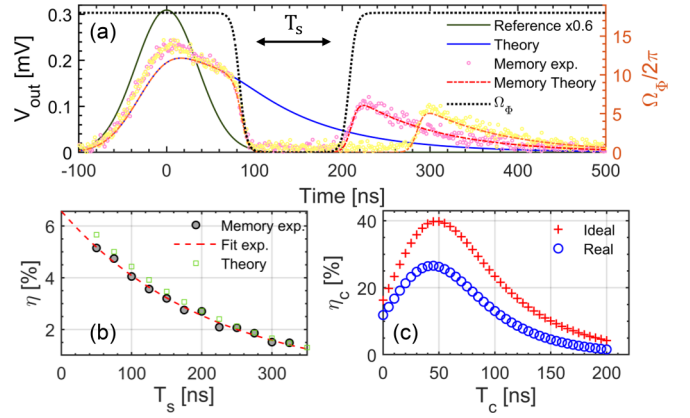


FIG. 4. EIT microwave memory with a single atom. (a) Stored light of the pulse. The dark green and blue solid lines represent the reference and slow light. The dynamic control of the parametric modulation is shown in the black dotted line. The pink (yellow) empty circles after $T_s = 125$ (200) ns show the stored-and-retrieval pulse. The theoretical prediction of stored light is depicted with a red (orange) dash-dotted line. (b) η (gray solid circles) varies with T_s . The theoretical prediction of η is shown in green empty squares. The red dashed line is the decay fit of the experimental data. (c) η_c varies with the modulation turn-off time T_c . The red plus-sign markers denote the ideal case, and the blue empty circles denote the real case.

system has the potential to serve as an on-demand single-photon source as it relies on the utilization of single-atom EIT.

To enhance memory efficiency, replacing the open transmission line with a semi-infinite transmission line prevents the retrieved pulse from emitting in the undesired direction. Enhancing the coherence of the metastable state by eliminating the inverse Purcell effect could also improve memory efficiency. Figure 4(c) depicts the theoretical study of the captured efficiency η_c of the resonator, defined as the ratio of the photon number in the resonator $\langle N_R \rangle$ to $\langle N_p \rangle$, as a function of the time T_c when turning off the modulation. In an ideal scenario ($\kappa = \gamma_\Phi = 0$), η_c can reach 40%, while in real situations, it can achieve up to 25%. Note that the storage efficiency of all the schemes [32–35] is limited by the small D , where a larger D is crucial for higher storage efficiency. Adding more atoms can enhance the optical depth. However, the two-photon scheme [33,34] must contend with photon switching and four-wave mixing effects, which degrade EIT and quantum memory fidelity under large D [25,56]. Our scheme avoids these issues and demonstrates the potential for scalability and high-efficiency quantum memory implementation.

Due to the controllable group velocity of the probe pulse [23,57], we can manipulate the shape of the retrieved probe pulse by the intensity of the parametric modulation in the retrieved process. The retrieved pulses via different turned-on Ω_Φ are depicted in Fig. 5. With the stronger Ω_Φ , the shape of the pulse becomes sharper. With the weaker Ω_Φ , the shape of the pulse becomes flatter due to the reduction of the group velocity.

In conclusion, this study presents the experimental demonstration of slow and stored light phenomena using a Λ -type superconducting artificial atom. The Λ -type atom is real-

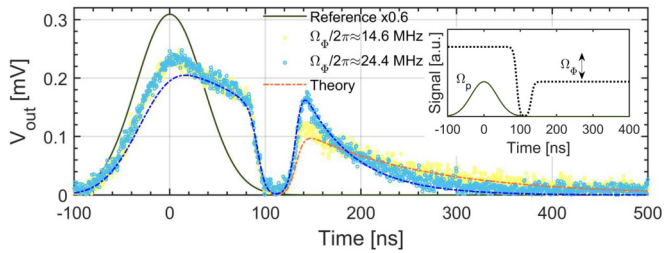


FIG. 5. Pulse shaping phenomenon. The retrieved pulse shape after $T_s = 40$ is manipulated with $\Omega_p/2\pi = 14.6$ and 24.4 MHz, respectively. The inset shows the pulse sequence.

ized through a detuned coupled qubit-resonator system with parametric modulation. A Gaussian probe pulse under continuous parametric modulation attains transparency and shows a

significant slowing-down effect. By adiabatically switching off the parametric modulation, a portion of the Gaussian pulse is successfully stored in the resonator. After a designated storage time, the pulse, with its shape controllable, is retrieved back to the transmission line by switching on the modulation with varying magnitudes. Our work paves the way for exploring various optical quantum memory schemes [58,59] and advancing quantum information processing in superconducting circuits.

W.T.L. acknowledges support from the Center for Quantum Technology, Hsinchu 30013, Taiwan. This work was supported by the National Science and Technology Council in Taiwan through Grants No. NSTC-112-2112-M-008-039, No. NSTC-113-2112-M-008-006, No. MOST-111-2639-M-007-001-ASP, No. NSTC-111-2923-M-008-004-MY3, and No. NSTC-113-2628-M-008-006-MY3.

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