High-efficiency coherent microwave-to-optics conversion via off-resonant scattering

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Quantum transducers that can convert quantum signals from the microwave to the optical domain are a crucial optical interface for quantum information technology. Coherent microwave-to-optics conversions have been realized with various physical platforms, but all of them are limited to low efficiencies of less than 50%—the threshold of the no-cloning quantum regime. Here we report coherent microwave-to-optics transduction using Rydberg atoms and off-resonant scattering technique with an efficiency of $82 \pm 2\%$ and a bandwidth of about 1 MHz. The high conversion efficiency is maintained for microwave photons ranging from thousands to about 50, suggesting that our transduction is readily applicable to the single-photon level. Without requiring cavities or aggressive cooling for the quantum ground states, our results would push atomic transducers closer to practical applications in quantum technologies.

Coherent and efficient transduction of microwaves into optical light plays a critical role in developing quantum technologies. For instance, to build a large-scale quantum network with superconducting quantum computers1–4, we need a transducer capable of transducing gigahertz microwave into terahertz optical light, which offers low transmission loss in room-temperature environments5. Moreover, the optical domain provides access to a suite of well-developed quantum optical tools, including highly efficient single-photon detectors and long-lived quantum memories6. Notably, access to a single-photon detector will facilitate the detection and imaging of weak microwave signals with potential applications in astronomy, medicine and other fields. To realize these applications, a coherent microwave-to-optics transducer with near-unity efficiency and large bandwidth is essential6–7.

Compared with classical transducers, a high-efficiency quantum transducer plays a more crucial role in preserving the fragile quantum state of information. For example, the quantum capacity of a bosonic channel is finite only if its photon transmissivity is greater than 50% (ref. 8), and thus, a conversion efficiency above this threshold will be necessary for any applications of transferring quantum states within the no-cloning regime without post-selection8. Several promising platforms have been proposed and implemented to realize microwave upconversion, including electro-optics9–12, optomechanics13–18, optically active dopants in solids19–24 and cold atoms25–27. Of these approaches, the highest efficiencies attained to date are 47% through optomechanics15 and 25% through electro-optics11. Both need high-quality cavities to achieve strong nonlinearities6, which inevitably limits the conversion bandwidth. Therefore, achieving near-unity microwave upconversion compatible with large bandwidths remains an outstanding challenge.

Cold atomic systems provide a natural setting for the realization of hybrid quantum interfaces. Cold atomic ensembles exhibit excellent cooperativity along phase-matched direction and large nonlinearity to achieve single-photon-level transduction19; therefore, optical cavities are not crucial for achieving high efficiency7. In addition, cold atoms coupled with superconducting resonators can store microwave photons in the long-lived hyperfine levels, and it is possible to combine the transduction of optical photons with quantum memories that will lay the basis for quantum network nodes8. Recently, microwave-to-optical transduction through a cold atomic ensemble has been demonstrated with a 5% conversion efficiency30. However, the maximum achievable efficiency is limited since atoms will evolve into a coherent population-trapped dark state and are decoupled from microwave or optical fields32.

Here we solve the difficulties faced by previous transduction experiments that use neutral atoms26–29 by creating a large atomic coherence with auxiliary fields to enhance the absorption of microwave photons. We do this by using the off-resonant six-wave mixing technique and a long, thin cylindrical atomic-gas medium. Our transducer demonstrates an unprecedented photon conversion efficiency of $82 \pm 2\%$, which is significantly higher than the quantum no-cloning limit, and maintains a large bandwidth of around 1 MHz at efficiencies above 50%. Moreover, our converter features excellent preservation of phase information during the conversion process, which is confirmed through optical heterodyne measurement, allowing for the faithful transduction of single-photon quantum states from the microwave to the optical domain.

Results

Off-resonant six-wave mixing scheme. We begin with a brief description of the six-wave mixing scheme for microwave-to-optics
conversion, with a six-level atomic system (Fig. 1a). In this scheme, the transduction of the input microwave field $\Omega_M$ into the optical field $\Omega_L$ is achieved through six-wave mixing assisted by four driven fields $\Omega_X$. The dynamics of the atomic system is governed by the following master equation for density operator $\rho$ (h is the reduced Planck constant),

$$\frac{d\rho}{dt} = -\frac{i}{\hbar} [H, \rho] + \mathcal{L}_P \rho + \mathcal{L}_{\text{deph}} \rho,$$

where $H$ is the Hamiltonian for an independent atom interacting with six external fields and $\mathcal{L}_P \rho$ and $\mathcal{L}_{\text{deph}} \rho$ represent the spontaneous emission of low-lying states and dephasing of atomic coherence involving the Rydberg states, respectively. In the paraxial approximation, we assume that the depletion of fields $\Omega_L$ and $\Omega_X$ in the medium is small and that the other four fields are treated in a self-consistent approach (Supplementary Section 1).

The frequency-mixing process is simulated through the numerical integration of Maxwell–Bloch equations under the steady-state condition. Here an ensemble of $^{85}$Rb atoms is under consideration. Figure 1b shows the calculated conversion efficiency $\eta$ (top) as a function of propagation distance $z$ for several detunings $\Delta_p$. The distinct behaviours of different detunings $\Delta_p$ in the spatial evolution of scattered fields can be explained by probability $P_D$ (Fig. 1b, bottom) in dark state $|D\rangle$ located at distance $z$, where $|D\rangle \propto (\Omega_M \Omega_X^* |1\rangle - \Omega_X \Omega_M^* |3\rangle + \Omega_X^* \Omega_M |5\rangle)$. For near-resonant scattering ($|\Delta_p| \ll \Gamma$), the atomic population in $|D\rangle$ increases with the buildup of photon conversion along the propagation direction. The input and output fields evolve without further interaction with the medium, and thus, $\eta$ saturates when almost all the atoms are trapped in the dark state.

For off-resonant scattering ($|\Delta_p| \gg \Gamma$), a two-photon transition consisting of detuned fields $\Omega_M$ and $\Omega_L$ establishes an effective coupling on the $|1\rangle \rightarrow |3\rangle$ transition. In the absence of the microwave field $\Omega_M$, the effective field and auxiliary field $\Omega_L$ create quantum coherence between the ground state $|1\rangle$ and Rydberg state $|4\rangle$ through coherent population trapping (CPT). The large atomic coherence $\rho_{4i}$ significantly prevents the system from being trapped in $|D\rangle$. As shown in Fig. 1b (bottom), $P_D$ is maintained below 30% within more than a hundred of the absorption lengths ($l_{abs} = \Gamma/4\zeta_i$, where $\Gamma$ is the decay rate of state $|6\rangle$ and $\zeta_i$ is the coupling constant at the $|1\rangle \rightarrow |6\rangle$ transition). Thus, the energy oscillates back and forth between the input microwave field and the upconverted optical field, making it possible to choose the propagation distance to maximize the conversion efficiency $\eta_{\text{max}}$ (Fig. 1b, top).

Furthermore, we investigate the optimal parameters for improving the efficiency of off-resonant scattering. We extract the maximum efficiency $\eta_{\text{max}}$ from the spatial evolution of scattered fields within over a hundred absorption lengths. Figure 1c shows the maximum conversion efficiency $\eta_{\text{max}}$ as a function of laser detunings $\Delta_p$ and $\Delta_s$ as well as the Rydberg-state dephasing rate $\gamma$. A small detuning $|\Delta_s| \approx \Gamma$, which lessens the reabsorption of the converted optical field inside the atomic ensemble, can increase the conversion efficiency. With an optimized detuning $\Delta_s$, the conversion efficiency $\eta_{\text{max}}$ increases with the decrease in dephasing rate $\gamma$. Here $\eta_{\text{max}}=0.85$ can be achieved with the parameters $|\Delta_p, \Delta_s, \gamma|$, optical depth (OD)} of $\{50, 50, 0.02\}$, 2000, $\gamma=0.002\Gamma$, $\Gamma=0.017\Gamma$ and $b=28.7$.

**Experimental setup.** We implement our microwave-to-optical transducer with an ensemble of cold $^{85}$Rb atoms released from a two-dimensional magneto-optical trap (MOT) to obtain a large OD $\{50, 50, 0.02\}$. Figure 2a shows a simplified diagram of the experimental setup: full details are included in Methods. The fields $\Omega_M$, $\Omega_X$ and $\Omega_M$ collinearly propagate along the axis and counterpropagate with the fields $\Omega_L$ and $\Omega_S$, which are derived from a single 480 nm laser. The microwave fields $\Omega_L$ and $\Omega_M$ from two microwave generators (R&S SMF100A), are combined with a power combiner just before the circular-polarization horn antenna. All the input lasers are focused onto the front end of the cigar-shaped atomic ensemble to increase the conversion area of the microwave and mitigate the polarization shift along with the Gaussian beam propagation. The fields $\Omega_L$ and $\Omega_M$, with opposite circular polarization, are separated by a quarter-wave plate and polarization beamsplitter. The detailed parameters of the six fields and relevant electric dipole moments

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**Fig. 1** | Theoretical analysis of microwave-to-optics conversion via off-resonant scattering. a. Energy-level configuration. Level $|1\rangle$ is a ground state. Levels $|2\rangle$ and $|6\rangle$ are two low-lying states with decay rates $\Gamma$ and $\Gamma'$, respectively. Levels $|3\rangle$, $|4\rangle$ and $|5\rangle$ are three Rydberg states with dephasing rate $\Gamma$. Energy-level configuration. Level $|1\rangle$ a
Fig. 2 | Experimental demonstration of microwave-to-optics conversion in cold atoms. a, Experimental setup and time sequence. Six-wave mixing (SWM) is performed by collinearly propagating fields along the z axis in a cigar-shaped atomic cloud. In each experimental cycle, the atomic coherence is established by auxiliary fields \( \Omega_a \), \( \Omega_b \), and \( \Omega_c \) after switching off the MOT and optical pumping (OP). A microwave pulse \( \Omega_m \) (-37 GHz) emitted from a circularly polarized antenna scatters off the coherence with field \( \Omega_a \), generating an optical pulse \( \Omega_L \) (~780 nm). The co-propagating fields \( \Omega_a \) and \( \Omega_b \) are separated using a polarizing beamsplitter (quarter-wave plate (QWP) + polarization beamsplitter (PBS)) and measured by photomultiplier tubes (PMT1 and PMT2), and the dichroic mirror (DM) separates the red light from blue light. b, Temporal waveforms of the input microwave pulse (black) and output optical pulses at \( \Delta \omega/2\pi = 0.2 \) (0.5) MHz are denoted as \( \Omega_L \) (\( \Omega_C \)). The 'SWM' block in a yields the square pulse in b. Transmission is scaled by the optical power converted with 100% efficiency. The bottom panel depicts the relative phase of a heterodyne signal for the phase-modulated microwave. The solid line is the input sine modulation of 100 kHz and 0.8 amplitude, and blue circles are experimental data extracted from the numerical phase detection. c, Spectra of transmission \( T_h \) (blue) and generated optical power \( P_h \) (red) at \( \Delta \omega/2\pi = 0.1 \) MHz. \( T_h \) is fitted to \( \exp(-a\tau) \), with absorption coefficient \( a \propto \text{Im}(\varphi) \) and the atomic polarization \( \varphi \) of the microwave-dressed four-level system. The spectrum of \( P_h \) is fitted to a Lorentzian function. d, \( P_h \) versus optical depth for off-resonant (red) and near-resonant (blue) scatterings at \( \Delta \omega/2\pi = 0.16 \) MHz. The symbols represent the experimental data, and the solid lines are theoretically simulated curves. The fitting parameters \( \Omega_m, \Omega_a, \Omega_b, \Delta \omega/\gamma, \gamma, \Gamma, \Delta \) are \( 2\pi \times (2.10, 8.30, 0.94, 12.50, 6, 0.30, 0.08, 0.10, 0.01, 0.01, 0.01, 0.01, 1) \) MHz. The error bars in c and d indicate 1σ standard error from three measurements.

### Table 1 | Six external fields and electric transition dipole moments

| Field | \( f \) or \( \lambda \) | Transition | Polarization | Waist (\( \mu \m) | \( |d_{\parallel}| \) (\( e\hbar \)) | Peak Rabi frequency |
|-------|-----------------|------------|--------------|----------------|-----------------|-------------------|
| \( \Omega_a \) | -384.2 THz | \( |1\rangle \leftrightarrow |2\rangle \) | \( \sigma^+ \) | 56(3) | 2.990 | \( 2\pi \times 3.30(2) \) MHz |
| \( \Omega_b \) | (780.2 nm) | \( |1\rangle \leftrightarrow |6\rangle \) | \( \sigma^+ \) | NA | 1.220 | NA |
| \( \Omega_c \) | -623.5 THz | \( |2\rangle \leftrightarrow |3\rangle \) | \( \sigma^- \) | 54(3) | 0.006 | \( 2\pi \times 9.20(4) \) MHz |
| \( \Omega_c \) | (480.8 nm) | \( |5\rangle \leftrightarrow |6\rangle \) | \( \sigma^- \) | 54(3) | 0.013 | \( 2\pi \times 13.20(6) \) MHz |
| \( \Omega_a \) | 36.705 GHz | \( |3\rangle \leftrightarrow |4\rangle \) | \( \sigma^- \) | NA | 363.600 | \( 2\pi \times 0.94(1) \) MHz |
| \( \Omega_d \) | 36.907 GHz | \( |4\rangle \leftrightarrow |5\rangle \) | \( \sigma^- \) | NA | 667.300 | NA |

For each field used in our experiment, the table lists the corresponding frequency\( f \), polarization, waist, dipole moment \( |d_{\parallel}| \) for relevant electric transition and the estimated peak Rabi frequency.

are presented in Table 1. The intensities of \( \Omega_a \) and \( \Omega_b \) are measured with two photomultiplier tubes (PMT; Hamamatsu, H10720-20). A laser-line bandpass filter is placed in front of the PMT to separate the stray noise photons, and the average time-dependent signals are recorded by a 5 GHz high-speed digital scope (R&S RTE1024).

The whole experiment is periodically run with a repeat rate of 100 Hz, which consists of 7.3 ms MOT loading time followed by a 2.7 ms conversion window (Fig. 2a, top left). During the conversion window, a bias magnetic field of 6.4 G is added along the z axis. The laser-cooled atoms are optically pumped to a specific Zeeman state \( |S_{\parallel}m_s, F=2, m_f=2 \rangle \) (\( F \) and \( m_s \) denote the atomic hyperfine energy levels and sublevels, respectively). Subsequently, the microwave pulse \( \Omega_m \) (with a duration of \( T = 10 \mu s \)) is emitted into the atomic ensemble for upconversion with a 5 \( \mu s \) delay after the auxiliary fields are switched on, where the delay guarantees that atomic coherence between states \( |1\rangle \) and \( |4\rangle \) is established.
Coherent microwave upconversion. We carry out the experiment following the theoretical simulation. The auxiliary fields $\Omega_3$ and $\Omega_{\perp}$ are blue-detuned from the corresponding atomic transition by 40.0 and 4.8 MHz, respectively. As shown in Fig. 2b (top), the input square-modulated microwave pulse has a rise and fall time of around 5 ns. First, we scan the detuning $\Delta_\perp$ of $\Omega_{\perp}$ across the $|1\rangle\leftrightarrow|3\rangle$ two-photon resonance and simultaneously measure the transmission of field $\Omega_3$ and power of the converted field $\Omega_L$ (Fig. 2c). The transmission $T_3$ exhibits a double-peak shape primarily due to the effect of the microwave-dressed electromagnetically induced absorption (EIA). The spectrum of the converted field ($P_L$) features a pronounced peak at around $\Delta_\perp = -40$ MHz. After that, we vary the medium length by blocking the trapping laser beam of the MOT with an aperture, and the focus of the lasers is maintained at the fore end of the ensemble. Figure 2d (red dots) corroborates that the converted field ($P_L$) reaches the maximum at an OD of around 63. For comparison, we also carry out the experiment in the near-resonant scheme. The maximum converted field decreases to only one-third that of the off-resonant scheme. The converted field starts to attenuate at larger ODs, which is mainly due to the reabsorption of the resonant field $\Omega_L$ (Supplementary Section V). The solid curves in Fig. 2d represent the theoretical simulations, which are in good agreement with the experiment.

As shown in Fig. 2b (top), the generated laser field $\Omega_L$ exhibits an exponential decay profile in the falling edge. The decay time is about 0.18 ms, which agrees with the lifetime of the low-lying state $|6\rangle$ ($\tau = 1/\Gamma$). To verify the coherence property of this transducer, we modulate the phase of the pulse $\Omega_{\perp}$ with a sine function and then recover the phase modulation with optical heterodyne detection. The heterodyne measurement is performed between the converted signal $\Omega_3$ and a reference beam for a pulse duration of 100 ms, which is derived from the same laser as $\Omega_3$. The frequency difference between the two beating laser beams is 2 MHz. Figure 2b (bottom) shows that the phase information is almost perfectly transferred during the conversion with an average fidelity of 98%, confirming the phase-preserving nature of our convertor. The observed delay between the recovery and the input of phase modulation is mainly derived from the slow-light effects in the frequency-mixing process.

**Efficiency and bandwidth.** As shown in Fig. 3a, the converted power $P_L$ grows approximately linearly in the weak-field regime ($\Omega_M \ll \Omega_\perp$). The linearity starts to break down when $\Omega_M \approx \Omega_\perp$. Then, the converted power $P_L$ drops at higher microwave intensities ($\Omega_M \gg \Omega_\perp$). The photon conversion efficiency of our setup is calculated as $\langle \omega_M \rangle$ and $\langle \omega_\perp \rangle$ are the angular frequencies of optical and microwave photons, respectively,

$$\eta = \frac{P_L}{h\omega_L S_M/\hbar \omega_M}.$$  

We only consider the microwave photon incident on the conversion region, where the atomic ensemble and all the six fields overlap, and $S_M$ is the averaged cross section of the conversion medium. The conversion efficiency calculation is consistent with its definition based on the photon fluxes. In Fig. 3b, we obtain an average conversion efficiency of $\eta = 82\%$, with a standard deviation of 2% and an average uncertainty of 7%. The input microwave pulse contains a mean photon number ranging from 50 to 6,400, as calculated by $I_M S_M T/\hbar \omega_M$.

To analyse the conversion bandwidth, we measure the efficiency as a function of detuning of the microwave field. Two sample micro-
wave spectra and their fits to the Lorentz function are depicted in Fig. 3c. The full-width at half-maximum (FWHM) is ~0.77 MHz at the peak efficiency of about 82% (grey circles). Figure 3d shows the FWHM as a function of the peak efficiency in the microwave spectrum. The spectrum has an FWHM value of around 1 MHz in the weak-field regime. Due to power broadening, the FWHM grows close to 4.7 MHz with a higher microwave intensity. The conversion bandwidth in our study is several to dozens of times larger than the values reported using electro-optics\(^1\), rare-earth ions ensemble\(^{12,23}\) and optomechanics\(^{15}\) approaches, illustrating the broadband conversion ability of atomic transducers.

**Discussion.** Our atomic transducer operates with the continuous-wave auxiliary fields in a steady-state atomic polarization. An all-resonant six-wave mixing approach was experimentally realized earlier\(^{5,6}\), where a conversion efficiency of around 5% was reported. Compared with these experiments, we made several improvements to achieve a higher conversion efficiency. We overcome the main drawback of the all-resonant approach by realizing a simplified off-resonant scheme (theoretically proposed elsewhere\(^2\)): the conversion efficiency saturates in the all-resonant approach because the distribution in the dark state is large and even approaches to one under the condition of a large OD. The dark state decouples from all the external fields; therefore, the absorption of microwave \(\Omega_c\) is small when the distribution in the dark state is large. In contrast, we prepare a significant atomic coherence between the metastable states \(|1\rangle\) and \(|4\rangle\) with the off-resonant auxiliary fields, and thus, a high conversion efficiency is achievable because the distribution in the dark state is negligible even in a large OD system (Fig. 1b). To achieve a high-efficiency conversion atomic transducer, large ODs and low Rydberg-state dephasing rates are the two necessary conditions. Unlike the previous transducer with a dense atomic cloud of small size, our large ODs are achieved by implementing the two-dimensional MOT configuration with a cylindrical trapping volume\(^4\), thereby maintaining a relatively low density to minimize the imperfections due to Rydberg–Rydberg interactions. Besides the low atomic density, the Rydberg-state dephasings are suppressed by reducing the stray magnetic fields with three pairs of Helmholtz coils, as well as by lifting the Zeeman degeneracy with a stable bias magnetic field.

At present, as shown in Fig. 3a, the resolvable microwave pulse containing around 50 photons is primarily limited by the background-noise fluctuation of the PMT detector. In principle, with low-noise single-photon counters and better optical filters, the microwave-to-optics conversion can be performed at the single-photon level. In Supplementary Section 6, we estimate the number of optical photons converted by the microwave background and it is about 0.8 at a temperature of 300 K. Therefore, the effect of thermal photons is negligible in most cases and contributes a fluctuation of about 2% in the worst case in our experiments. The thermal microwave reduces with a decrease in temperature, for instance, the number of converted photons becomes 0.1 at a temperature of 39 K, and thus, the effect of the microwave background can also be neglected in a single-photon experiment when the temperature is lower than 39 K. Moreover, a larger Rabi frequency \(\Omega_c\) can further improve the conversion bandwidth in our scheme\(^1\).

In summary, we have realized an atomic transducer with high efficiency via off-resonant six-wave mixing in free space. With large ODs and low Rydberg-state dephasing rates, we have obtained a coherent microwave-to-optics conversion efficiency of 82 ± 2% and a bandwidth of about 1 MHz; the conversion efficiency exceeds the 50% threshold value for practical applications. The scheme may have various potential applications. Besides neutral-atoms-based transduction, the off-resonant scattering scheme can be used to increase the efficiency of rare-earth-crystal-based transduction, such as three-wave mixing using spin transitions for the ground states\(^{12,20}\) or optically excited states\(^{22}\). The microwave-to-optics conversion approach can be further developed to perform at the single-photon level. Combined with high-efficiency single-photon detectors, the scheme can be used in detecting and imaging weak microwave signals, which has various applications in astronomy, medicine and other fields.

Notably, the high efficiency and broad bandwidth achieved in our scheme meet the optical interface requirement for superconducting qubits. As pioneering works have achieved coherent coupling between Rydberg atoms and the microwave field of various superconducting devices\(^{45–48}\), we can expect atomic transducers to convert single-photon quantum states in a cryogenic environment\(^{42–44}\), providing a critical component of large-scale hybrid quantum networks. For instance, this transduction approach can be used in an ensemble of atoms coherently coupled to the microwave field of an on-chip coplanar waveguide resonator, resulting in the directional emission of optical photons even without an optical cavity\(^5\). The microwave photon residence in the cavity increases the interaction time of frequency mixing, and it relaxes the demand for medium thickness compared with free-space conversion. Moreover, this Rydberg transducer operates in the steady-state atomic polarization associated with the Rydberg level coupled to the microwave field (that is, \(|4\rangle\) in our scheme), leading to a collective enhancement of microwave transition in the single-photon regime. Meanwhile, the resonant dipole–dipole interaction between Rydberg atoms becomes negligible in the case of a single microwave photon. Therefore, the atomic transducer developed here may find practical applications in large-scale hybrid quantum networks.

**Online content**

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Methods

Conversion efficiency. The conversion efficiency $\eta$ is defined as the ratio of the converted optical photon flux to the input microwave photon flux. In the theoretical analysis of Fig. 1, the efficiency is given by

$$\eta = \frac{|\langle \Omega | e^{i\phi(t)} | \Omega \rangle |^2}{|\langle \Omega | e^{i\phi(t)} | \Omega \rangle |^2_{\text{in}}}$$

(3)

where $\phi$ represents the ratio of the coupling constants $\zeta$, $C$, $\Omega$, $\Omega_{\text{in}}$ and $\Omega_{\text{out}}$ are the Rabi frequencies of the input microwave field and converted optical field, respectively.

Dark state. The approximate dark state of the Hamiltonian in equation (1) is of the form $|D\rangle = C (|S_{\text{R}}^2, \Omega_{\text{in}}^2 \rangle |1\rangle - |S_{\text{R}}^2, \Omega_{\text{in}}^2 \rangle |3\rangle + |S_{\text{R}}^2, \Omega_{\text{in}}^2 \rangle |5\rangle)$ for $\Omega_{\text{in}} = - \Omega_{\text{in}}^2 / (\Omega_{\text{in}}^2 + \Omega_{\text{out}}^2)$, where the normalization constant is defined as

$$C = \frac{1}{\sqrt{\Omega_{\text{in}}^2 + \Omega_{\text{out}}^2}}$$

(4)

The probability for the atoms populated in the dark state $|D\rangle$ is defined as

$$P_D = \text{Tr} [\rho_0(z) \eta(z)]$$

(5)

where $\eta$ is the steady-state solution of equation (1) at the given position $z$.

Cold-atom preparation and Rydberg laser system. The cold $^{87}$Rb medium with a typical size of $4 \times 4 \times 24$ mm$^3$ serves as the microwave-to-optical transducer. The relevant energy levels are $|1\rangle = |S_{\text{R}}^2 = 2, m_s = 2\rangle, |2\rangle = |F = 3, m_f = 3\rangle, |3\rangle = |F = 3, m_f = 1\rangle, |4\rangle = |F = 1, m_f = 1\rangle, |5\rangle = |F = 2, m_f = 1\rangle$, respectively. For the two-dimensional MOT, the typical OD is 140 for $|5\rangle$ transition, which yields an atomic number density around $1.2 \times 10^{10} \text{cm}^{-3}$. Each trapping laser beam has a power of 25 mW and a radius of 1.6 cm. The total power of the two repump laser beams is about 35 mW with the same radius as the trapping laser beam. The gradient of the quadruple magnetic field is 8 G cm$^{-1}$ with the same radius as the trapping laser beam. The microwave-to-optics conversion is defined as

$$\frac{1}{\sqrt{\Omega_{\text{out}}}}$$

(6)

where $\Omega_{\text{in}}(t)$ (or $\Omega_{\text{out}}(t)$) represents the input (converted) phase-modulation waveform in the optical heterodyne measurements and $t_s$ is the delay time.

Data availability

The data supporting the results in this study are available within the paper and Supplementary Information. The raw datasets generated during the study are too large to be publicly shared, but they are available from the corresponding authors upon reasonable request.

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Author contributions

K.-Y.L. and H.Y. designed the experiment. H.-T.T., K.-Y.L., S.-Y.Z. and X.-D.Z. conducted the raw-data collection. H.-T.T., Z.-X.Z, X.-H.L. and S.-Z.Y. carried out the experiments. H.-T.T., K.-Y.L. and H.Y. wrote the paper, and all the authors discussed the paper’s contents. H.Y. and S.-L.Z. supervised the project.

Competing interests

The authors declare no competing interests.

Additional information

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