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Coherent Coupling between Microwave and Optical Fields via Cold Atoms *

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We demonstrate a long-coherent-time coupling between microwave and optical fields through cold atomic ensembles. The phase information of the microwave field is stored in a coherent superposition state of a cold atomic ensemble and is then read out by two optical fields after 12 ms. A similar operation of mapping the phase of optical fields into a cold atomic ensemble and then retrieving by microwave is also demonstrated. These studies demonstrate that long-coherent-time cold atomic ensembles could resonantly couple with microwave and optical fields simultaneously, which paves the way for realizing high-efficiency, high-bandwidth, and noiseless atomic quantum converters.

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Coherent coupling between microwave and optical fields via atomic coherence plays an important role in quantum conversion. Many proposals have been put forward to realize microwave-to-optical conversion via cold ground-state atoms[1–5] and cold Rydberg atoms.[6–9] Nowadays, coherent microwave-to-optical conversion has been experimentally realized by six-wave mixing in cold Rydberg atoms[10,11] and by three-wave mixing in room-temperature ground-state atoms.[12] To realize the full quantum state transfer between microwave and optical fields without thermal noise via atomic coherence, quantum converters should work in a cryogenic environment. Cold ground-state atoms, which are insensitive to detrimental adsorbate fields and do not require Rydberg-excitation lasers, still maintain coherence for several seconds in a superconducting coplanar microwave resonator.[13,14] Therefore, cold ground-state atoms as a medium to couple microwave and optical photons deserve special attention. To realize high-efficiency and high-bandwidth quantum converters proposed by Huo,[5] microwave and optical fields resonantly coupling with a cold atomic ensemble is a prerequisite.

In this Letter, we report an experimental observation of coherent coupling between microwave and optical fields via a cold atomic ensemble. By resonantly driving the atomic hyperfine states with microwave and optical fields simultaneously, the Rabi oscillation with a damping time of 0.15 ms is observed. The total Rabi frequency depends on the relative phase between microwave and optical fields, confirming the coherent coupling between microwave and optical fields. To the best of our knowledge, this is the first time such a coherent coupling in cold atomic systems has been reported. Inspired by the coherent coupling experiment reported by Lekavicius *et al.*,[15] we map the phase information of the microwave field into a coherent superposition state of a cold atomic ensemble and then read out 12 ms later with two optical fields. The opposite process is also demonstrated. Similar coherent coupling between a superconducting microwave resonator and an optical ring cavity via a cold atomic ensemble can enable the implementation of an atomic quantum memory[2,16,17] and a microwave-to-optical quantum converter.[5]

Our experimental setup is schematically shown in Fig. 1, where a cloud of ^{87}Rb atoms are cooled by a standard magneto-optical trap (MOT) followed by magnetic compression and optical molasses.[18,19] Three pairs of Helmholtz coils are used to cancel out the terrestrial magnetic field and provide a quantization axis along the incident direction of the optical fields. The bias field is about 0.1 Gauss, which allows the selective coupling of the transition between $|F = 1, m_F = 0\rangle$ and $|F = 2, m_F = 0\rangle$ by the optical fields and the microwave field, with F being the total atomic angular momentum and m_F the magnetic quantum number. The repumping laser is turned off later than the cooling laser, which leads to preparing all the atoms in state $|F = 2\rangle$. Then the atoms in state $|F = 2, m_F = 0\rangle$ are coherently transferred to $|F = 1, m_F = 0\rangle$ by a π microwave pulse. Af-

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ter blowing off the residual atoms in state $|F = 2\rangle$, cold atomic ensembles are initially prepared in state $|F = 1, m_F = 0\rangle$. Population information is determined with the fluorescence collected by a photodiode after illumination of cooling lasers. To eliminate the total population fluctuation, populations in states $|F = 1\rangle$ and $|F = 2\rangle$ are measured simultaneously for normalization.

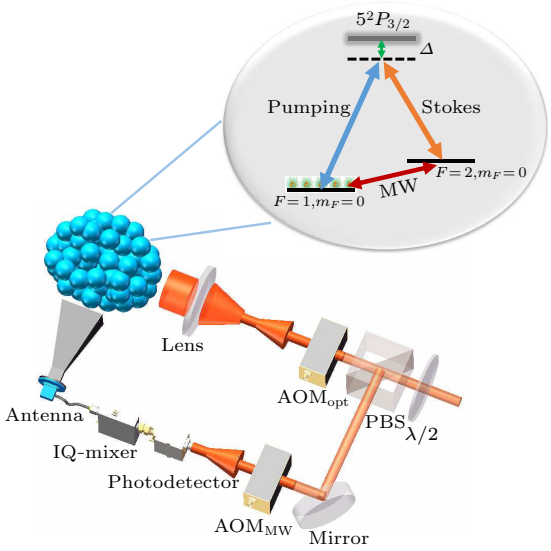

Fig. 1. The simplified experimental setup for observing coherent coupling between microwave (MW) and optical fields. Hyperfine levels $|F = 1, m_F = 0\rangle$ and $|F = 2, m_F = 0\rangle$ of $5^2S_{1/2}$ of ^{87}Rb are coupled by a microwave field and two optical fields (pumping and Stokes fields), respectively. The single-photon detuning Δ between the optical fields and the excited state $5^2P_{3/2}$ of ^{87}Rb is about 2.5 GHz. The 6.8 GHz microwave field is generated by detecting the beat signal between the two optical fields using a fast photodetector. The phase of the microwave field is controlled by the IQ-mixer. Optical and microwave pulses are generated by $\mathrm{AOM_{opt}}$ and $\mathrm{AOM_{mw}}$, respectively.

Two optical fields (pumping and Stokes fields) and one microwave field couple with the two ground states $|F = 1, m_F = 0\rangle$ and $|F = 2, m_F = 0\rangle$, which form a closed three-level atomic system in the triangle-type configuration. The bare states $|F = 1, m_F = 0\rangle$, $|F = 2, m_F = 0\rangle$ and $5^2P_{3/2}$ are denoted by $|0\rangle$, $|1\rangle$, and $|2\rangle$, respectively. The pumping field is locked to the transition $|F = 2\rangle \rightarrow |F' = 3\rangle$ of ^{85}Rb by the saturated absorption frequency stabilization technique. The Stokes field is locked to the pumping field with a stable beating frequency with a bandwidth of less than 1 Hz by the optical phase-locked loop technique.[20] The two optical fields are set to be two-photon resonance and large single-photon detuning ($\Delta \sim 2.5$ GHz) from the $5^2P_{3/2}$ excited state. The relative phase between the two optical fields is determined by the relative phase of the RF waves that drive two acoustic-optic modulators (AOMs). After passing through the two AOMs, the two optical fields are overlapped to preserve the relative phases and then split by a polarized beam splitter (PBS). One of the lasers is used as optical coupling and the other is used as microwave coupling. $\mathrm{AOM_{opt}}$ and $\mathrm{AOM_{mw}}$, shown in Fig. 1, are used for the generation or gating of optical pulses and microwave pulses, respectively. The 6.8 GHz microwave field is generated by detecting the beat signal between the two optical fields using a fast photodetector with bandwidth of 33 GHz. This ensures that the microwave and the double optical fields are phase locked. The phase of the microwave field is controlled by an IQ-mixer (AM4080A), as shown in Fig. 1. Note that all the AOMs mentioned above are driven by ultrastable radio sources (DG4162, bandwidth <15 Hz) synchronized with an atomic clock (FS725, SRS).

Here we present a basic theory describing the coherent coupling between microwave and optical fields. First of all, we briefly describe the well-known Raman transition. The Rabi frequencies of the pumping and Stokes fields are defined as $\Omega_{\mathrm{P}}(t) = \mu_{13}\mathcal{E}_{\mathrm{P}}(t)/\hbar$ and $\Omega_{\mathrm{S}}(t) = \mu_{23}\mathcal{E}_{\mathrm{S}}(t)/\hbar$, with the electric dipole transition moments μ_{ij} and the electric fields $\mathcal{E}_{\mathrm{P,S}}(t)$ of the optical fields. Thus the Hamiltonian of the three-level Λ system in the basis $\{|0\rangle, |1\rangle, |2\rangle\}$ under the interaction picture and the rotating-wave approximation reads

$$H_{\mathrm{R}} = \frac{\hbar}{2}\begin{pmatrix} 0 & 0 & \Omega_{\mathrm{P}}e^{i\phi_{\mathrm{P}}} \\ 0 & 2\delta & \Omega_{\mathrm{S}}e^{i\phi_{\mathrm{S}}} \\ \Omega_{\mathrm{P}}e^{-i\phi_{\mathrm{P}}} & \Omega_{\mathrm{S}}e^{-i\phi_{\mathrm{S}}} & 2\Delta \end{pmatrix}, \quad (1)$$

where δ is the two-photon detuning, and $\phi_{\mathrm{opt}} = \phi_{\mathrm{P}} - \phi_{\mathrm{S}}$ is the relative phase between the two optical fields, with ϕ_{P} and ϕ_{S} being the phases of the pumping and Stokes fields, respectively. From now on, we assume Δ is large (i.e., $\Delta \gg \Omega$) and $\delta = 0$ (two-photon resonance). Under these conditions, it is natural to restrict the Hilbert space to the relevant states $|0\rangle$ and $|1\rangle$ and to describe their dynamics by a 2×2 effective Hamiltonian H_{eff}. The effective Hamiltonian is given by

$$H_{\mathrm{eff}} = \frac{\hbar}{2}\begin{pmatrix} \Delta_{\mathrm{eff}} & \Omega_{\mathrm{eff}}e^{i\phi_{\mathrm{opt}}} \\ \Omega_{\mathrm{eff}}e^{-i\phi_{\mathrm{opt}}} & -\Delta_{\mathrm{eff}} \end{pmatrix}, \quad (2)$$

where $\Omega_{\mathrm{eff}} = \Omega_{\mathrm{P}}\Omega_{\mathrm{S}}/(2\Delta)$ is the effective Rabi frequency coupling the levels $|0\rangle$ and $|1\rangle$, and $\Delta_{\mathrm{eff}} = (\Omega_{\mathrm{P}}^2 - \Omega_{\mathrm{S}}^2)/(4\Delta)$ is identified with the ac Stark shift associated with the two optical fields.

Next, we briefly introduce the one-photon microwave-induced transition. The Rabi frequency of the microwave is defined as $\Omega_{\mathrm{mw}} = \mu_{12}\mathcal{B}_{\mathrm{mw}}/\hbar$, with the magnetic dipole transition moment μ_{12} and the magnetic field $\mathcal{B}_{\mathrm{mw}}(t)$ of the microwave. Thus the Hamiltonian of the two-level system in the basis $\{|0\rangle, |1\rangle\}$ under the interaction picture and the

rotating-wave approximation reads

$$H_{\rm mw} = \frac{\hbar}{2}\begin{pmatrix} \Delta_{\rm mw} & \Omega_{\rm mw}e^{i\phi_{\rm mw}} \\ \Omega_{\rm mw}e^{-i\phi_{\rm mw}} & -\Delta_{\rm mw} \end{pmatrix}, \quad (3)$$

where $\Delta_{\rm mw} = \delta$ and $\phi_{\rm mw} = \phi_{\rm opt}$ at the PBS in Fig. 1.

Under the conditions $\Delta_{\rm mw} = \delta = 0$ and $\Delta_{\rm eff} = 0$, the total Rabi frequency induced by microwave and optical fields is given by

$$\Omega_{\rm T} = \Omega_{\rm eff} + e^{-i\phi_{\rm a}}\Omega_{\rm mw}. \quad (4)$$

The interference pattern of Rabi frequencies $\Omega_{\rm eff}$ and $\Omega_{\rm mw}$ can be observed by scanning the phase $\phi_{\rm a}$, which is added to the microwave field.

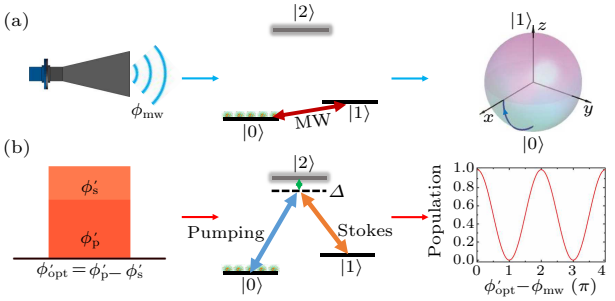

Fig. 2. (a) One microwave field, with a phase $\phi_{\rm mw}$, applies a $\pi/2$ Rabi pulse to the ground states $|0\rangle$ and $|1\rangle$ and effectively maps $\phi_{\rm mw}$ to a coherent superposition state of the ground states $|0\rangle$ and $|1\rangle$. (b) Two optical fields, with relative phase $\phi'_{\rm opt} = \phi'_{\rm P} - \phi'_{\rm S}$, apply a $\pi/2$ Rabi pulse to the aforementioned coherent superposition state. Population in state $|1\rangle$ features sinusoidal oscillation as a function of $\phi'_{\rm opt} - \phi_{\rm mw}$, effectively reading out the microwave phase.

In the experiments of Lekavicius *et al.*,[15] dark states formed by two microwave fields or two optical fields are used for the coherent coupling between optical and microwave fields. The relative phase information of the two microwave fields is firstly mapped into the dark states and is then read out by two optical fields. Similarly, an opposite process is also demonstrated. As illustrated in Fig. 2, our scheme for phase information storage and reading out of optical and microwave fields exploits the coherent superposition state of the ground states $|0\rangle$ and $|1\rangle$ instead of dark states in a cold atomic ensemble. The phase information $\phi_{\rm mw}$ of the microwave field is firstly mapped into the relative phase θ of a superposition state

$$|\Psi\rangle = C_0|0\rangle + e^{i\theta}C_1|1\rangle, \quad (5)$$

where C_0 (C_1) is the real probability amplitude of state $|0\rangle$ ($|1\rangle$) (see Fig. 2(a)). After a certain storage time, the microwave phase is read out by two optical fields (see Fig. 2(b)). Similarly, the relative optical phase can be encoded into the superposition state $|\Psi\rangle$ and then retrieved by a microwave field after a certain storage time.

Here we focus on the resonant coupling case in our experiments, which is essential to realize high-efficiency and high-bandwidth quantum converters as proposed by Huo.[5] The transition between the clock states $|0\rangle$ and $|1\rangle$ is in first order insensitive to magnetic fields. We set the frequency difference of two optical fields to be 6.8346826109 GHz. To cancel out the ac Stark shift,[18] the pump power and the Stokes fields are set to 15.6 mW and 24.4 mW with diameter 10 mm, which are kept in the following experiments.

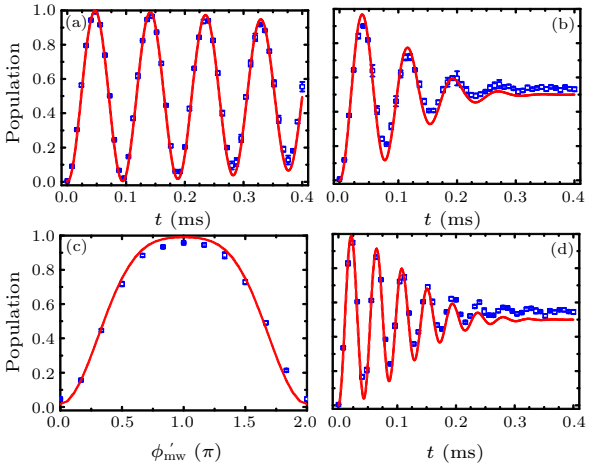

Fig. 3. Proof of coherent coupling between microwave and optical fields. Observation of microwave-field-induced Rabi oscillations (a) and optical-field-induced Rabi oscillations (b) between states $|0\rangle$ and $|1\rangle$ (blue squares with error bars), and fits of the damping oscillations (red solid lines). (c) Transfer efficiency versus the relative phase $\phi'_{\rm mw}$ between optical and microwave fields, which is changed by an IQ-mixer. The blue squares with error bars are the experimental data, while the red solid line is the theoretical simulation result. (d) Observation of constructive Rabi oscillations between states $|0\rangle$ and $|1\rangle$, which are resonantly driven by microwave and optical fields simultaneously (blue squares with error bars), and fit of the damping oscillation (red solid line).

To demonstrate the coherent coupling between microwave and optical fields, we first measure the Rabi frequencies of microwave-field-induced Rabi oscillations and optical-field-induced Rabi oscillations by driving states $|0\rangle$ and $|1\rangle$ with variable microwave pulse lengths (cf. Fig. 3(a)) or optical pulse lengths (cf. Fig. 3(b)). The observed Rabi frequencies are $\Omega_{\rm mw} = 2\pi \times 10.7$ kHz with a damping time of $\tau_{\rm mw} \approx 1$ ms and $\Omega_{\rm opt} = \Omega_{\rm eff} = 2\pi \times 12.8$ kHz with a damping time of $\tau_{\rm opt} \approx 0.15$ ms. Then we drive states $|0\rangle$ and $|1\rangle$ with fixed microwave and optical pulse length $T_{\rm mw+opt} = 20\,\mu$s, while varying the microwave phase $\phi'_{\rm mw}$ from 0 to 2π by an IQ-mixer. As shown in Fig. 3(c), the population in state $|1\rangle$ depends on $\phi'_{\rm mw}$, revealing the coherence of coupling between microwave and optical fields. The theoretical transfer efficiency $P = [1 - \cos(\Omega_{\rm T}T_{\rm mw+opt})]/2$ fits very well with the experimental data, where $\Omega_{\rm T} = \Omega_{\rm opt} + e^{-i(\phi'_{\rm mw}+\phi_{\rm path})}\Omega_{\rm mw}$. It is worth noting that there is a constant relative phase $\phi_{\rm path} = -1.01\pi$ between microwave and optical fields. This is caused by different

propagation distances between microwave and optical fields.[21] Finally, we drive states $|0\rangle$ and $|1\rangle$ with variable microwave and optical pulse lengths when $\phi'_{\rm mw}+\phi_{\rm path}=0$ and observe the constructive Rabi oscillations with $\Omega_{\rm T}=2\pi\times 23.1\,{\rm kHz}$ and a damping time of $\tau_{\rm mw+opt}\approx 0.15\,{\rm ms}$ (cf. Fig. 3(d)). The dampings in Figs. 3(a), 3(b) and 3(d) are mainly caused by the inhomogeneity of the microwave and optical fields. The microwave field is more homogeneous than the optical fields, thus the damping time of the microwave coupling in Fig. 3(a) is longer than that of optical Raman transitions in Fig. 3(b). The Rabi frequencies of the microwave and optical fields are the same so that the damping in Fig. 3(d) is mainly dominated by the inhomogeneity of optical fields like that in Fig. 3(b). It is possible to make these damping times the same by simultaneously enlarging the beam diameter of the Raman lasers and increasing the power of the optical fields.

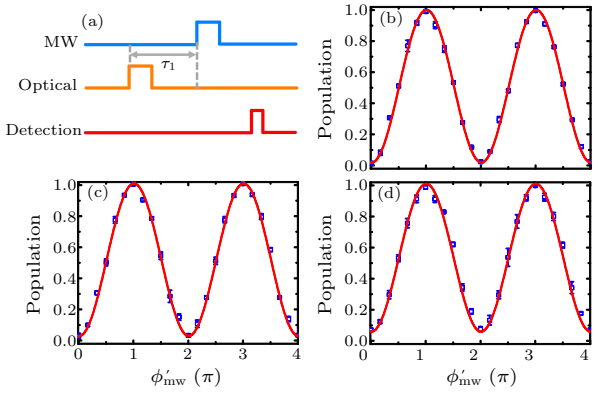

Fig. 4. Phase information storage of optical fields and read-out by microwave field. (a) Pulse sequence. The optical fields' Rabi pulse maps the relative phase $\phi_{\rm opt}$ to a superposition state of $|0\rangle$ and $|1\rangle$. After certain storage time τ_1, the microwave Rabi pulse retrieves the phase information of the superposition state. Population in state $|1\rangle$ features sinusoidal oscillations as a function of $\phi'_{\rm mw}$ with storage time (b) $\tau_1=0\,{\rm ms}$, (c) $\tau_1=6\,{\rm ms}$, and (d) $\tau_1=12\,{\rm ms}$. The blue squares with error bars are the experimental data, while the red solid lines are the fitting results.

We now turn to storing phase information of the optical fields and then reading it out by a microwave field. We first initialize the cold atomic ensemble in the state $|0\rangle$ and then apply a resonant $\pi/2$ optical Rabi pulse to create a superposition state given in Eq. (5), with $C_0=C_1=1/\sqrt{2}$ and with relative phase θ mapped by the relative phase $\phi_{\rm opt}$ of the two optical fields. To retrieve the phase information as indicated in Fig. 4(a), we then apply a resonant $\pi/2$ microwave Rabi pulse with a well-defined phase $\phi'_{\rm mw}$ changed by an IQ-mixer. The superposition atomic state transforms to a new state

$$|\Psi\rangle=\frac{1}{2}[(1-e^{i(\phi'_{\rm mw}-\theta)})|0\rangle-ie^{-i\phi'_{\rm mw}}(1+e^{i(\phi'_{\rm mw}-\theta)})|1\rangle]. \tag{6}$$

The population in state $|1\rangle$ depends on the relation between θ and $\phi'_{\rm mw}$, as shown in Eq. (6). The sinusoidal oscillations of population in state $|1\rangle$ as a function of $\phi'_{\rm mw}$ in Figs. 4(b)–4(d) demonstrate that the relative phase θ is read out efficiently by the microwave field. The corresponding storage times are $\tau_1=0\,{\rm ms}$, $\tau_1=6\,{\rm ms}$ and $\tau_1=12\,{\rm ms}$ with associated contrasts (defined as $(I_{\rm max}-I_{\rm min})/(I_{\rm max}+I_{\rm min})$) 0.96, 0.94 and 0.88, respectively, which shows a dephasing time of $\approx$150 ms. The decay of this Ramsay interference is mainly caused by the fluctuations of magnetic field. The released atom clouds fly out of the detecting region after around 12 ms, and thus we cannot perform further experiments to show the decay of the visibility versus the interrogation time τ_1.

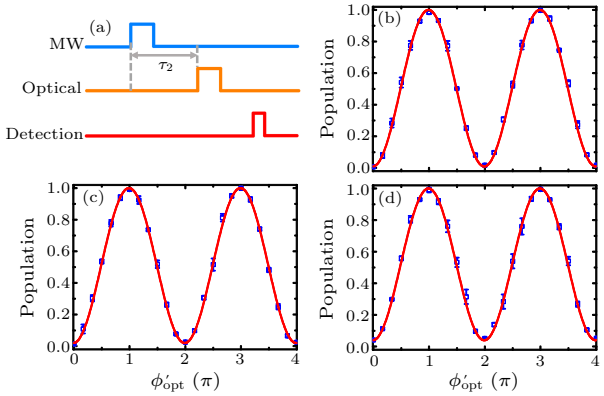

Fig. 5. Phase information storage of microwave field and read-out by optical fields. (a) Pulse sequence. The microwave Rabi pulse maps the phase $\phi_{\rm mw}$ to a superposition state of $|0\rangle$ and $|1\rangle$. After certain storage time τ_2, the optical-field Rabi pulse retrieves the phase information of the superposition state. Population in state $|1\rangle$ features sinusoidal oscillations as a function of $\phi'_{\rm opt}$ with storage times (b) $\tau_2=0\,{\rm ms}$, (c) $\tau_2=6\,{\rm ms}$, and (d) $\tau_2=12\,{\rm ms}$. The blue squares with error bars are the experimental data, while the red solid lines are the fitting results.

The opposite process is used to store phase information of the microwave field and to read it out by the optical fields. As shown in Fig. 5(a), a $\pi/2$ microwave Rabi pulse with phase $\phi_{\rm mw}$ creates a coherent superposition state of $|0\rangle$ and $|1\rangle$, which effectively encodes $\phi_{\rm mw}$ to the phase of atomic spin coherence. After a certain storage time, a $\pi/2$ optical Rabi pulse with relative phase $\phi'_{\rm opt}$ is used to read out the microwave phase. Here $\phi'_{\rm opt}$ is changed by varying the relative phase of the two RF sources, which are used to drive the two AOMs (not shown in Fig. 1) of the optical fields. The phase storage times in Figs. 5(b)–5(d) are 0 ms, 6 ms and 12 ms, respectively. The corresponding contrasts are 0.98, 0.96 and 0.92, respectively, yielding a dephasing on the same timescale of $\approx$200 ms.

In summary, we have experimentally observed long-coherent-time coupling between microwave and optical fields via a cold atomic ensemble. Phase information storage and read-out of microwave and optical fields via cold atomic ensembles have been demonstrated.

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