Non-reciprocity and quantum correlations of light transport in hot atoms via reservoir engineering

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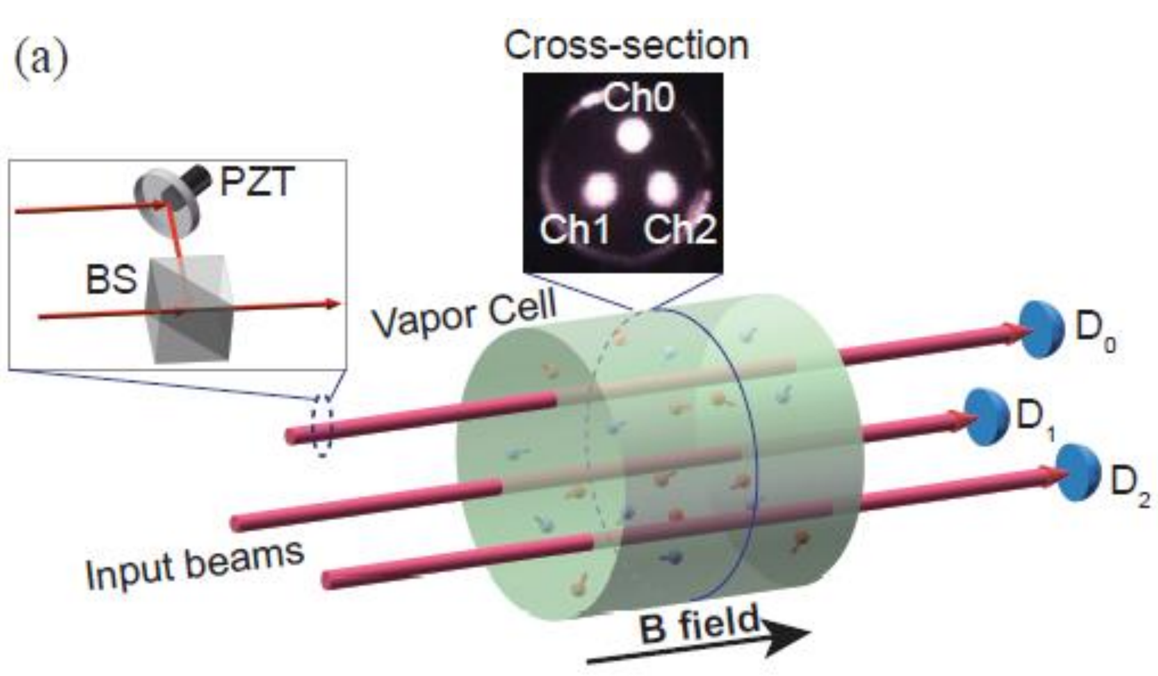
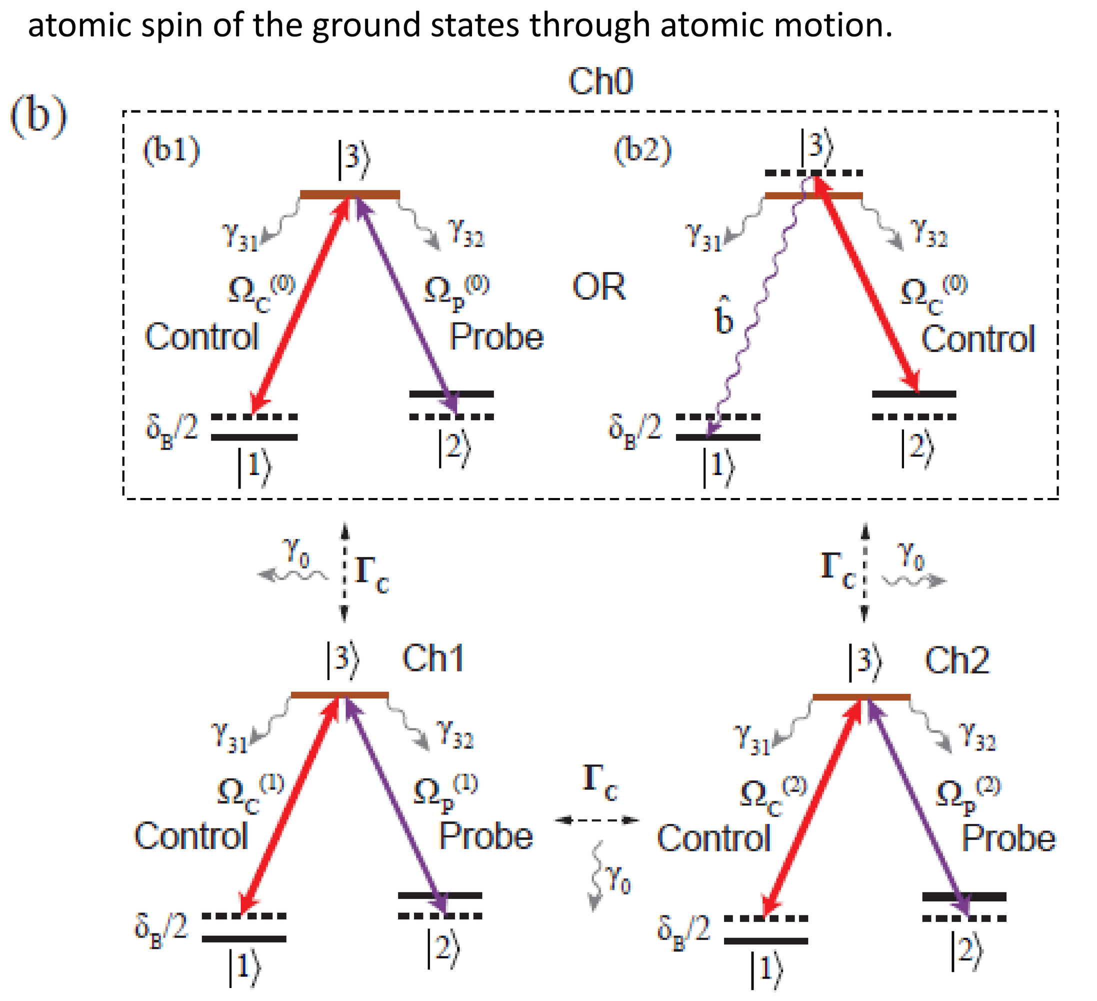
Abstract: The breaking of reciprocity is a topic of great interest in fundamental physics and optical information processing applications. We demonstrate non-reciprocal light transport in a quantum system of hot atoms by engineering the dissipative atomic reservoir. Our scheme is based on the phase-sensitive light transport in a multi-channel photon-atom interaction configuration, where the phase of collective atomic excitations is tunable through external driving fields. Remarkably, we observe inter-channel quantum correlations which originate from interactions with the judiciously engineered reservoir. The non-reciprocal transport in a quantum optical atomic system constitutes a new paradigm for atom-based, non-reciprocal optics, and offers opportunities for quantum simulations with coupled optical channels.

Experimental Setup

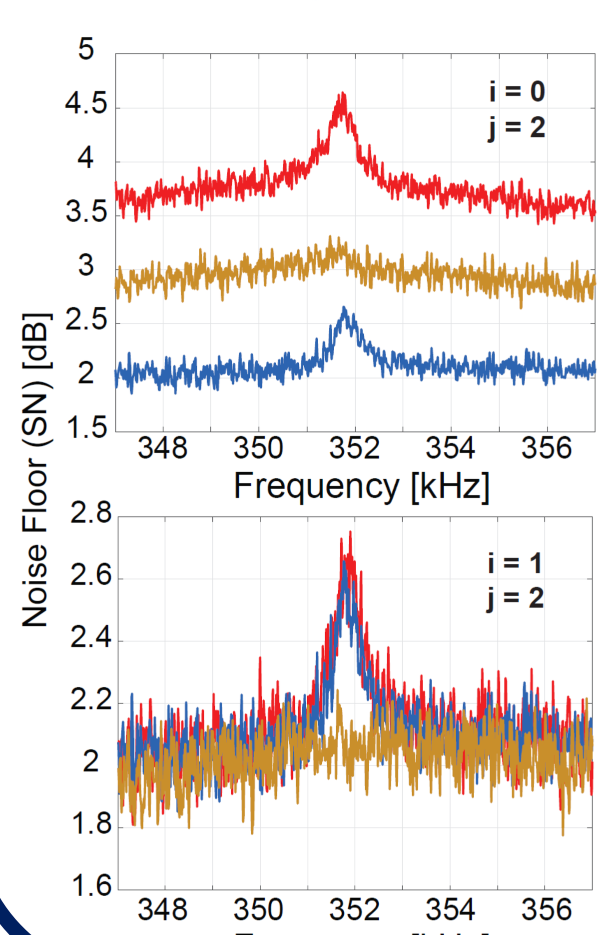


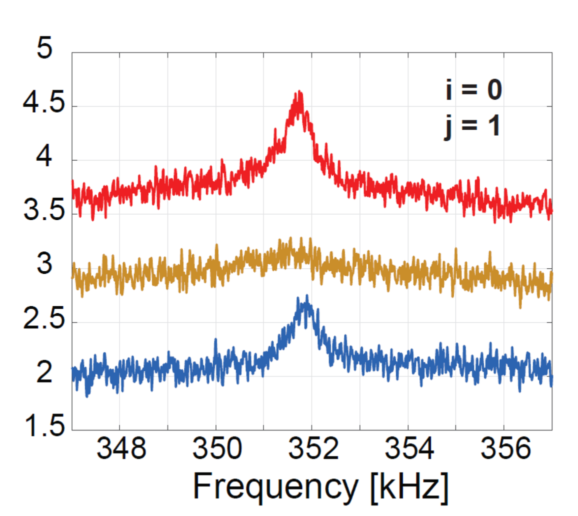
Experiment schematics. Three spatially separated optical channels propagate in a warm paraffin-coated Rb^{87} vapor cell under EIT interaction. The inter-channel couplings are mediated by the mixing of atomic spin of the ground states through atomic motion.



The three-level scheme in three channels. The ground states are Zeeman sublevels of F = 2, and the excited state is F = 1 of the 87Rb[87] D1 line. In the measurements of quantum fluctuation, all three weak probes are removed as shown in (b2) (Ch1 and Ch2 are not shown).

Quantum correlations





Var(X_i) Var(X_j) Var($\frac{X_i - X_j}{\sqrt{2}}$)

Criteria for quantum correlation:

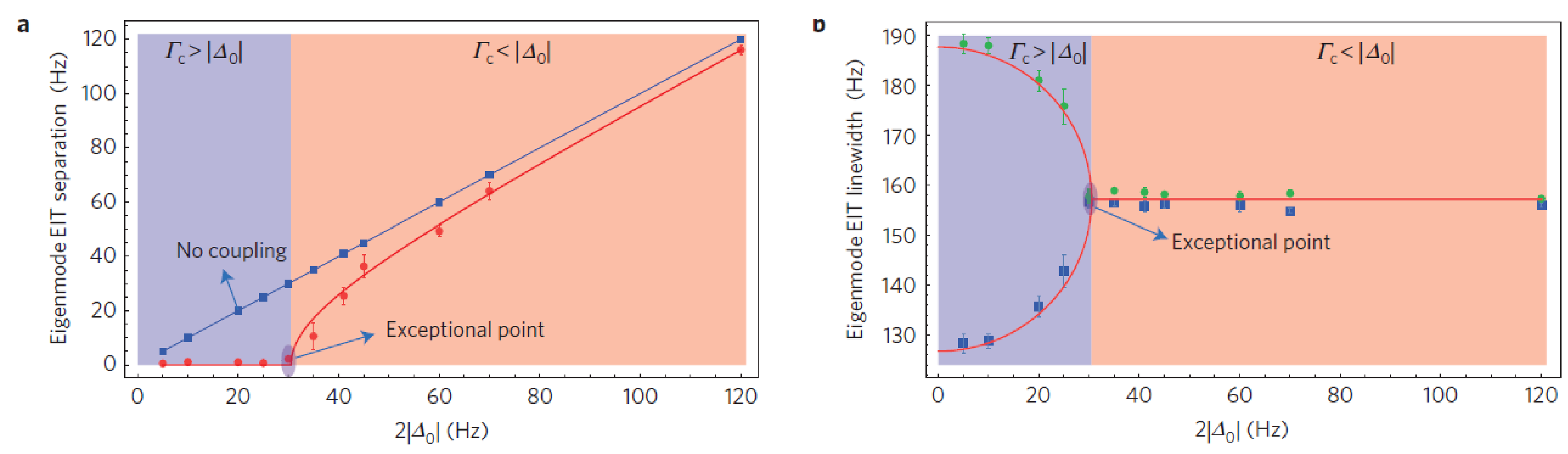
$$\mathrm{Var}\left(\frac{\hat X_i-\hat X_j}{\sqrt{2}}\right)+\mathrm{Var}\left(\frac{\hat P_i+\hat P_j}{\sqrt{2}}\right) < \frac{\mathrm{Var}(\hat X_i)+\mathrm{Var}(\hat X_j)}{2}+\frac{\mathrm{Var}(\hat P_i)+\mathrm{Var}(\hat P_j)}{2}$$

The noise spectrum of P_i, P_j, and $P_i \pm P_j$ are identical to X_i, X_j, $X_i \mp X_j$.

Non-Hermitian Coupling Hamiltonian

① **Atoms:** $H' = \begin{bmatrix} |\Delta_0| - i\gamma'_{12} & i\Gamma_c \\ i\Gamma_c & -|\Delta_0| - i\gamma'_{12} \end{bmatrix}$

Eigenvalues: $\omega_\pm = -i\gamma'_{12} \pm \sqrt{\Delta_0^2 - \Gamma_c^2}$



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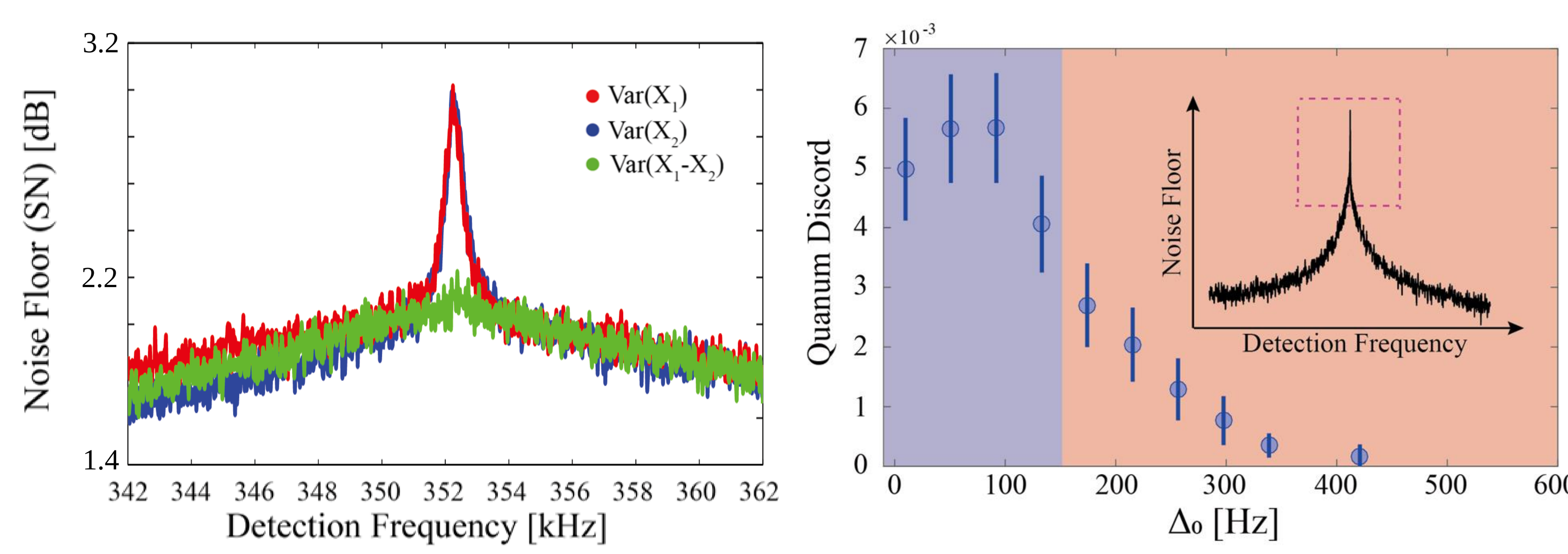
② **Photons(1):** CH1: $\hat H_1 \propto \hat a_1^\dagger \hat S^\dagger + h.c.$; CH0: $\hat H_2 \propto \hat b^\dagger \hat S + h.c.$ } Two-mode squeezing: $H \propto \hat a_l^\dagger \hat b_u^\dagger + h.c.$



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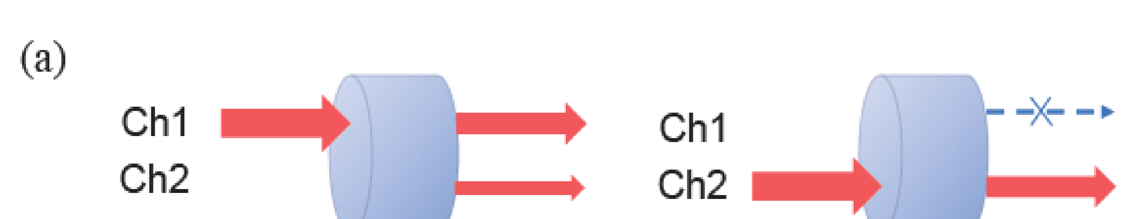
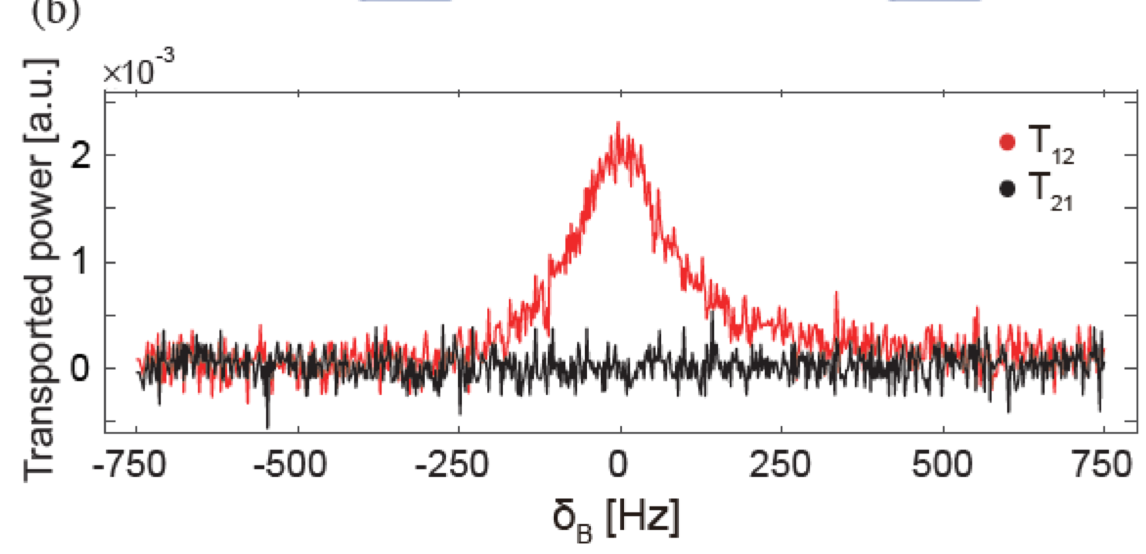
③ **Photons(2):** CH1: $\hat H_1 \propto \hat a_1^\dagger \hat S^\dagger + h.c.$; CH2: $\hat H_2 \propto \hat a_2^\dagger \hat S^\dagger + h.c.$ } Beam splitter: $H \propto \hat a_1^\dagger \hat a_2 - h.c.$



$$H_{eff} \propto \sum_{i,j}^{i\neq j} \hat a_i^\dagger \hat a_j e^{-i\varphi_{ij}} - \hat a_i \hat a_j^\dagger e^{i\varphi_{ij}}$$



(a) Schematics of the non-reciprocal transport.
(b) Transport spectrum. The two-photon detuning δ_B is proportional to the applied common magnetic field.

Red curve T_{12} is the transported power from Ch1 to Ch2 when injecting the weak probe in Ch1. Black curve T_{21} is the transported power from Ch2 to Ch1 when injecting the weak probe in Ch2. The local phase of all three channels is set to be: $\theta_0 = 0$, $\theta_1 = 0$ and $\theta_2 = \pi$. The input power of the probe in each channel is 50 μW. The input power of the control in each channel is 500 μW. The cell temperature is 60C.

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