Electromagnetically Induced Transparency Based Cross-Phase Modulation at Attojoule Levels

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Abstract

We report the first experimental demonstration of electromagnetically induced transparency (EIT) based cross-phase modulation (XPM) at few-hundred-photon levels. A phase shift of 0.005 rad of a probe pulse modulated by a signal pulse with an energy of 100 attojoules, equivalent to ~400 photons, was observed in a dark spontaneous-force optical trap. The experimental data show the single-photon-level XPM phase shift is ~1 × 10⁻⁴ rad, which is in good agreement with the theoretical prediction. This work offers exciting prospects to the realization of EIT-based XPM scheme at the single-photon level and benefits experimental development in few-photon applications of EIT-based techniques for quantum optics and quantum information science.

Motivation

- The ability to achieve strong single-photon nonlinearities is significant for applications in quantum information processing and quantum computation.
- To enhance nonlinear optical effects, electromagnetically induced transparency (EIT) is a well-known phenomenon in which resonant absorption in an optically dense medium can be eliminated by quantum interference [1,2].
- In 2009, EIT-based all-optical switching has been realized in a hollow fiber with light pulses containing a few hundred photons [3]. However, EIT-based cross-phase modulation (XPM) at few-photon levels has yet to be demonstrated.

Theoretical Model

- The theoretical expressions for the N-type EIT-based XPM phase shift and transmission of the probe pulse are [4]

\[
T = \exp \left[ -n_{\text{eff}} L \gamma_3 \left( \Omega_1^2 |r|^2 + |\Omega_2|^2 + 2 \gamma_3 \Omega_1 \Omega_2 \right) \right]
\]

\[
\Delta^n_{\text{XPM}} = -n_{\text{eff}} L \gamma_3 \left( \Omega_1^2 + |\Omega_2|^2 - 4 \Omega_1 \Omega_2 - 4 \Omega_1 |\Omega_2|^2 \right)
\]

\[
\gamma_3 \text{ and } \gamma_4 \text{: Rabi frequencies of the coupling and signal transitions, respectively.}
\gamma_3 \text{ and } \gamma_4 : \text{Total coherence decay rates out of excited states [3] and [4], respectively.}
\gamma_3 - \text{ The ground-state decoherence rate.}
\gamma_{\text{eff}} - \text{ The optical density for the probe transition.}
\]

Results and Discussion

- The symbols and solid lines represent the measurement data and theoretical predictions, respectively.
- The XPM phase shift and figure of merit as a function of signal photon numbers.
- The parameters for the theoretical curves:

\[
n_{\text{eff}} \lambda L = 16, \quad \gamma_3 = 0.24, \quad \gamma_4 = 1.25 \Gamma, \quad \gamma_5 = 0.0025 \Gamma
\]

\[
\Gamma = 2\pi \times 6 \text{ MHz is the spontaneous decay rate.}
\]

Acknowledgment

Reference