Dynamic optical bistability in resonantly enhanced Raman generation


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We report observations of novel dynamic behavior in resonantly enhanced stimulated Raman scattering in Rb vapor. In particular, we demonstrate a dynamic hysteresis of the Raman scattered optical field in response to changes of the drive laser field intensity and/or frequency. This effect may be described as a dynamic form of optical bistability resulting from the formation and decay of atomic coherence. We have applied this phenomenon to the realization of an all-optical switch.

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It is now well known that the optical properties of atomic media may be dramatically altered if the atoms are placed into an appropriate quantum superposition of states, enabling, e.g., electromagnetically induced transparency (EIT) and lasing without inversion [1]. Such coherently prepared media can also exhibit extremely large nonlinearity at very low light levels [2–6]. In this paper we demonstrate a novel form of nonlinearity—dynamic optical bistability—using resonantly enhanced Raman generation in warm Rb vapor [7]. The observed bistable behavior results from the formation of a long-lived coherence in the atomic ensemble due to the strong light-atom interaction provided by a double-Λ interaction scheme, which can be approximated as two strong pump fields Ω_{1,2} interacting with a three-level atom as shown in Fig. 1(a) [8]. Strong Raman gain is produced with this scheme, generating a pair of correlated Stokes and anti-Stokes fields E_{1,2} [9–11]. We find dynamic optical bistability in the form of hysteresis in the response of either of the Raman fields to sufficiently fast variation in the corresponding pump field.

Optical bistability has been extensively studied for several decades (see [12,13] for reviews), and observed in many systems. Most typically, optical bistability occurs with a nonlinear medium placed in an optical cavity, such that there is more than one stable condition of output light intensity from the cavity for a given intensity of near-resonant input light, i.e., there is a hysteresis in the effective cavity transmission. Optical bistability with a cavity has been observed with various two- and three-level atomic systems serving as the nonlinear medium [14–19]. Optical bistability has also been demonstrated without a cavity using degenerate four-wave mixing in atomic vapor with two counterpropagating laser beams [20,21]. In these latter experiments, the bistability arises from a dependence of phase-matching conditions on the magnitude of the output field [22].

The unique features of the present results are (i) optical bistability arises due to the formation of long-lived atomic coherence, which in turn depends on the amplitudes and phases of all four optical fields (Ω_{1,2} and E_{1,2}); and (ii) bistability is observed in a co-propagating laser geometry without a cavity. The steady-state amplitudes of both the Stokes and anti-Stokes fields are self-adjusted by the light-atom interaction, so that a generalized four-photon dark state is established that is decoupled from all optical fields. The generalized dark state in the double-Λ system is analogous to the dark state polariton employed in “stored light” in the single-Λ system [23–25], with the dynamics controlled by three relevant time scales. First, there is the characteristic time of atomic response to change in the pump fields, i.e., the time for atomic coherence to be created and modified. This time is given by the inverse bandwidth of the four-photon Raman process [9,10], and may be quite short,

$$\tau_R \propto \frac{\Delta}{|\Omega_1||\Omega_2|},$$

where Δ is the detuning of the off-resonant pump field Ω_{1,2} (see Fig. 1(a)). In our experiment, $\tau_R < 1 \mu s$ for typical values of the pump fields Ω_{1,2} and Δ.

The second relevant time scale characterizes the equilibration of the four-photon dark state, and hence the response time of the amplitudes and phases of the generated Raman fields. This time is determined by the optical pumping rate of the far-detuned pump field Ω_{1,2},

$$\tau_S \propto \frac{\Delta^2}{\gamma|\Omega_1|^2},$$

where γ is the relaxation rate of the excited state. For comparable values of the pump field powers, one has

![FIG. 1. (a) Three-level double-Λ scheme used in the experiment. The first diode laser LD1 (pump field Ω_{1}) is detuned by Δ ≈ 4 GHz to the blue side of the Rb transition F = 1 → F' = 2. The second laser LD2 (pump field Ω_{2}) is resonant with F = 2 → F' = 2. (b) Experimental setup.](image-url)
Thus all fields had linear polarization after passing through the atomic cell. To avoid retroreflection of either laser beam back into the cell, we employed a cylindrical glass cell filled with isotopically pure $^{87}\text{Rb}$ and 6 Torr of Ne buffer gas. We placed the cell inside a three-layer magnetic shield to reduce the influence of stray magnetic fields, and heated the cell to 106 °C, which corresponds to a Rb vapor density of $7 \times 10^{12}$ cm$^{-3}$. Since counterpropagating laser beams can produce mirror-like behavior, and then reaches a maximum and from the second laser on a polarizing beam splitter (PBS1). The polarizations of the two fields were then transformed by a quarter-wave plate into orthogonal circular polarizations before entering the Rb cell. The maximum available optical power for the lasers LD1 and LD2 was approximately 3 mW and 4 mW, respectively, with the laser beams focused inside the cell to diameters of about 200 μm.

For the chosen pump field polarizations and resonant atomic levels, each of the generated Raman fields had circular polarization, with the same chirality as the corresponding pump field. Thus all fields had linear polarization after passing through the second quarter-wave plate placed after the Rb cell, with the polarization of fields $\Omega_1$ and $E_1$ being orthogonal to $\Omega_2$ and $E_2$. All these fields were then combined at the second polarizing beamsplitter (PBS2) together with an additional beam from the first laser which propagated outside of the atomic cell. The frequency of this “bypass” field was shifted down by 80 MHz with respect to the field $\Omega_1$.

To study the dynamics of Raman generation, we varied the intensity of the off-resonant laser field $\Omega_1$ by modulating the voltage applied to the AOM at frequency $f_{\text{mod}}$, while the intensity and frequency of laser LD2 were kept constant. Figure 3(a) shows the observed dependence of the Stokes field amplitude $E_1$ on the corresponding pump field $\Omega_1$, for the case of very slow variations of $\Omega_1$ (i.e., $f_{\text{mod}} T_2 \ll 1$). One can see that the amplitude of the Stokes field exhibits threshold-like behavior, and then reaches a maximum (determined by the phase-matching conditions between all four optical fields). If the intensity of the pump field increases sufficiently, it drives the system out of the optimal conditions for Raman generation, and the amplitude of the generated field decreases. It is important to note that in the quasistatic case ($f_{\text{mod}} \ll 10$ Hz), the Raman generation threshold is the same regardless of the “direction” of the pump field’s change. Thus there is no hysteresis in the regime of low modulation frequency.

As shown in Figs. 3(b)–3(d), a hysteresis loop appears for the Stokes field amplitude as $f_{\text{mod}}$ increases. We define the “threshold” values $P_{\text{on}}$ and $P_{\text{off}}$ as the pump field powers at which Raman generation starts (for increasing $\Omega_1$) and ceases (for decreasing $\Omega_1$). Their dependence on $f_{\text{mod}}$ is pre-
sented in Fig. 4. One can see that the difference between $P_{\text{on}}$ and $P_{\text{off}}$ increases with the modulation frequency, and these threshold powers are reasonably fit by $P_{\text{on}} - P_{\text{th}} \sim \sqrt{f_{\text{mod}}}$ and $P_{\text{off}} - P_{\text{th}} \sim -\sqrt{f_{\text{mod}}}$, where $P_{\text{th}}$ is the threshold power for Raman generation in the cw regime. We can reproduce this scaling law by taking into account the delayed response of the generated Raman field to the pump field modulation, as characterized by the delay time $\tau_S$ [which depends on pump field power, see Eq. (2)]. This simple model yields

$$P_{\text{on,off}} \approx P_{\text{th}} \left( 1 \pm \frac{1}{2} \sqrt{f_{\text{mod}} \tau_S^4} \right),$$

where $\tau_S^4$ is the four-photon dark-state equilibration time in the vicinity of the Raman generation threshold. This expression is in good qualitative agreement with the experimental results. However, a more complete description of the threshold behavior will require treatment of the diffusion of coherently prepared atoms in and out of the optical interaction region [28,29].

At higher modulation frequencies ($f_{\text{mod}} > 1$ kHz), the measured peaks of the Raman field $E_1$ output differ for increasing and decreasing pump field $\Omega_1$, a result of changes in the four-photon phase-matching conditions (which determine optimal Raman generation) that are fast relative to $\tau_S$.

Two additional notes about the observed dynamic optical bistability: (i) we found Raman hysteresis similar to that shown in Fig. 3 by fixing the intensity of both pump lasers, tuning $\Delta$ to be near a cutoff frequency for Raman generation (see Fig. 2), and modulating the frequency of either of the pump fields; and (ii) we observed similar bistable behavior for the anti-Stokes field $E_2$, although this field was generally much weaker than $E_1$ because of large residual absorption.

As an example application of dynamic optical bistability, we demonstrated an all-optical switch in which the Raman field $E_1$ was turned on and off by briefly pulsing the intensity of the pump field above or below a median level (see Fig. 5). During the turn-on pulse, the strength of the pump field

FIG. 3. Differing degrees of observed hysteresis in the generated Raman Stokes field $E_1$ as the corresponding $\Omega_1$ pump field intensity is modulated at (a) 10 Hz (no hysteresis); (b) 150 Hz; (c) 1.2 kHz; (d) 4 kHz. Several (two to three) cycles are shown on each plot to demonstrate the reproducibility of the data, with arrows indicating the “direction” of change of the pump field. The off-resonant laser detuning $\Delta$ was approximately 4 GHz.

FIG. 4. Measured dependence on modulation frequency of the hysteresis threshold powers, $P_{\text{on}}$ and $P_{\text{off}}$, of the off-resonant pump field. The dashed lines indicate independent fits of $P_{\text{on}}$ and $P_{\text{off}}$ to $\sqrt{f_{\text{mod}}}$. Inset: Graphic definition of the manner in which $P_{\text{on}}$ and $P_{\text{off}}$ were determined from the hysteresis data.

FIG. 5. Demonstration of an all-optical switch using dynamic optical bistability. The Stokes field $E_1$ could be switched on and off (lower graph) by pulsing the pump field $\Omega_1$ (top graph). The duration of the $\Omega_1$ pulses was 40 $\mu$s; the plotted intensity of these pulses is normalized to their maximum value (≈2.5 mW) with a detuning $\Delta=4$ GHz.
$\Omega_1$ was long enough to establish significant atomic coherence, and thus to provide large Raman generation once $\Omega_1$ returned to its median value. Similarly, the duration of the turn-off pulse was long enough for the resonant $\Omega_2$ pump field to convert atomic coherence in the interaction region into anti-Stokes $E_2$ photons, in a process closely related to the release of stored light [10,11,23–25]. Thus the switching for both turn-on and turn-off can likely be made much faster with stronger pump fields.

In conclusion, we have studied the dynamics of resonantly enhanced Raman generation in a double-$\Lambda$ configuration in Rb vapor. We observed a novel form of dynamic optical bistability based on long-lived atomic coherence, which did not involve an optical cavity or an induced Bragg grating in the medium. This bistability can be easily adjusted with changes to the pump laser fields, which may assist practical applications. Realization of dynamic optical bistability may also be possible in condensed-matter systems [30–32]. As an example application, we used dynamic optical bistability to demonstrate a simple, all-optical switch.

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[8] Resonantly enhanced Raman scattering has also been observed for incoherent pump fields and atomic coherence created by an additional microwave field: H. Tang and W. Happer, Phys. Rev. Lett. 24, 551 (1970).