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13. ABSTRACT (Maximum 200 words) This report summarizes our work on the use of electromagnetically induced transparency to make new types of optical devices. Key accomplishments during this program period include the generation of the first single-cycle optical pulse, and the development of a radiation source with four octaves of bandwidth. In a second area of work we have demonstrated nonlinear optical processes at the lowest photon flux ever used.					
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STUDIES OF ELECTROMAGNETICALLY INDUCED TRANSPARENCY
AND ITS RELATION TO NONLINEAR OPTICS

FINAL TECHNICAL REPORT
(1 APRIL 2003 – 30 SEPTEMBER 2004)

S. E. HARRIS

OFFICE OF NAVAL RESEARCH

GRANT N00014-03-1-0599

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December 2004

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I. Statement of Problem Studied

The central theme of this work has been the use of electromagnetically induced transparency (EIT) for new types of nonlinear interactions and processes. We have emphasized work in two areas: (1) the generation of femtosecond pulses by phased and anti-phased molecular states, and (2) the demonstration of elementary nonlinear processes at low-light-levels. The work in both of these areas substantially extends the capabilities of optical scientists and engineers. Though we always think of optical fields as basically sinusoidal, they might, for example, soon be nearly triangular. Such waveforms may allow new types of optical-material interaction. The work on low-light-level nonlinear optics is ultimately aimed at the interaction of localized single photons. Though there is a long way to go here, electromagnetically induced transparency offers one of the most promising avenues.

The work in both areas reported here have been jointly supported by the Air Force Office of Scientific Research, the Air Force Research Laboratory and the Army Research Office. The work in area (2) has been jointly supported by the Multidisciplinary Research Initiative Program.

II. Summary of Most Important Results

The last several years have been very productive. Highlights of our work during this period include:

- (1) The development of a new light source, which was used to produce femtosecond-time-scale pulses with over an octave of optical bandwidth. These pulses were in turn used to demonstrate phase control of multi-photon ionization under conditions where ionization requires 11 photons of the lowest frequency of the spectra, or, five photons of the highest frequency.
A. V. Sokolov, D. R. Walker, D. D. Yavuz, G. Y. Yin, and S. E. Harris, "Femtosecond Light Source for Phase Controlled Multiphoton Ionization," *Phys. Rev. Lett.* **87**, 033402/1-033402/4 (July 2001).
- (2) We have invented a new technique for achieving a multiplicative increase in the total number of generated sidebands for a Raman process. When phase-corrected, these sidebands synthesize to a train of randomly times single-cycle pulses.
S. E. Harris, D. R. Walker, and D. D. Yavuz, "Raman Technique for Single-Cycle Pulses," *Phys. Rev. A* **65**, 021801-1/021801-4 (January 2002).
- (3) We have experimentally shown the use of rotational Raman generation with near-unity conversion efficiency. The spectrum consists of 37 coherent sidebands covering over 20,000 cm^{-1} of spectral bandwidth and ranging from 1.37 μm to 352 nm in wavelength.
D. D. Yavuz, D. R. Walker, G. Y. Yin, and S. E. Harris, "Rotational Raman Generation With Near Unity Conversion Efficiency," *Opt. Lett.* **27**, 769-771 (May 2002).
- (4) A new type of focusing phenomena has been experimentally demonstrated in our lab. In this regime the two-photon detuning from the Raman resonance controls the refractive index of the medium.
D. R. Walker, D. D. Yavuz, M. Y. Shverdin, G. Y. Yin, A. V. Sokolov, and S. E. Harris, "Raman Self-Focusing at Maximum Coherence," *Opt. Lett.* **27**, 2094-2096 (December 2002).
- (5) We have reported the experimental demonstration of a Raman technique that produces 200 sidebands, ranging in wavelength from 3 μm to 195 nm. This work showed mutual phase coherence among 15 visible sidebands covering 0.63 octaves of bandwidth.
D. D. Yavuz, D. R. Walker, M. Y. Shverdin, G. Y. Yin, and S. E. Harris, "Quasi-Periodic Raman Technique for Ultrashort Pulse Generation," *Phys. Rev. Lett.* **91**, 233602/1-233602/4 (December 2003).
- (6) We have demonstrated an efficient nonlinear optical process at an energy level at about 23 photons per square wavelength. This occurs in a rather unique system, which absorbs two photons, but which will not absorb a single photon.
D. A. Braje, V. Balic, G. Y. Yin, and S. E. Harris, "Low-Light-Level Nonlinear Optics with Slow Light," *Phys. Rev. A* **68**, 041801/1-041801/4 (October 2003).
- (7) In recent work we have demonstrated the generation of a train of single-cycle optical pulses, each with a pulse length of 1.6 fs. We believe that this is a major accomplishment.

III. Peer-Reviewed Publication List

D. D. Yavuz, D. R. Walker, and M. Y. Shverdin, "Spatial Raman Solitons," *Phys. Rev. A* **67**, 041803/1-041803/4 (April 2003).

D. R. Walker, D. D. Yavuz, M. Y. Shverdin, G. Y. Yin, and S. E. Harris, "A Quasiperiodic Approach to Ultrashort Pulses", *Optics & Photonics News* **14**, 46-51 (June 2003).

D. A. Braje, V. Balic, G. Y. Yin, and S. E. Harris, "Low-Light-Level Nonlinear Optics with Slow Light," *Phys. Rev. A* **68**, 041801/1-041801/4 (October 2003).

D. D. Yavuz, D. R. Walker, M. Y. Shverdin, G. Y. Yin, and S. E. Harris, "Quasi-Periodic Raman Technique for Ultrashort Pulse Generation," *Phys. Rev. Lett.* **91**, 233602/1-233602/4 (December 2003).

D. D. Yavuz, "Elimination of Feshbach Loss in a Bose-Einstein Condensate," *Opt. Comm.* **234**, 253-257 (February 2004).

M. Y. Shverdin, D. D. Yavuz, D. R. Walker, "(2+1)-Dimensional Stable Spatial Raman Solitons," *Phys. Rev. A* **69**, 031801/1-031801/4 (March 2004).

IV. Manuscripts Submitted, But Not Published

A. V. Sokolov, M. Y. Shverdin, D. R. Walker, D. D. Yavuz, A. M. Burzo, G. Y. Yin, and S. E. Harris, "Generation and Control of Femtosecond Pulses by Molecular Modulation" (*Journal of Modern Optics*, to be published)

M. Y. Shverdin, D. R. Walker, D. D. Yavuz, G. Y. Yin, and S. E. Harris, "Generation of a Single-Cycle Optical Pulse" *Phys. Rev. Lett.*, to be published).

S. N. Goda, M. Y. Shverdin, D. R. Walker, S. E. Harris, "Measurement of Fourier-Synthesized Optical Waveforms" (*Optics Letter*, to be published).

V. Papers and Presentations at Meetings

S. E. Harris, "*Photon Switching with Slow Light: Low-Light-Level Nonlinear Optics in Cold Atoms*," DAMOP, Boulder, Colorado (May 2003) [Invited].

S. E. Harris, "*Single Cycle Optical Pulses*," Agilent Labs, Palo Alto (May 2003) [Invited].

S. E. Harris, "*Quasi-Periodic Raman Technique*," Grand Targee Quantum Electronics Meeting, Wyoming (July 2003) [Invited].

D. Braje and S. E. Harris, "*Low Light Level Photon Switching with Slow Light*" 16th International Conference on Laser Spectroscopy (ICOLS03), Cairns, Australia (July 2003) [Poster].

D. Walker and S. E. Harris, "*Quasiperiodic Raman Technique for Ultrashort Pulse Generation*", Gordon Conference on Nonlinear Optics, New London, New Hampshire (July 2003) [Poster].

S. E. Harris, "*Quasiperiodic Raman Technique For Ultrashort Pulse Generation*," International conference on laser physics, Hamburg, Germany (August 2003) [Invited].

D. Yavuz, and D. Walker and S. E. Harris, "*Quasiperiodic Raman Technique For Ultrashort Pulse Generation*", Gordon Conference on Quantum Control of Light and Matter, South Hadley, MA (August 2003) [Poster].

M. Shverdin and S. E. Harris, "*Three Dimensional Stable Spatial Raman Solitons*," Gordon Conference on Quantum Control of Light and Matter, South Hadley, MA (August 2003) [Poster].

D. Braje, V. Balic and S. E. Harris, "*Photon Switching with Slow Light: Low-Light-Level Nonlinear Optics in Cold Atoms*," Gordon Research Conference, Mount Holyoke College, Massachusetts (August 2003) [Invited].

D. Braje and S. E. Harris, "*Low-Light-Level Nonlinear Optics in Cold Atoms*," Stanford Photonics Research Center, Stanford, CA (September 2003) [Invited].

M. Shverdin and S. E. Harris, "*Three Dimensional Stable Spatial Raman Solitons*," Stanford Photonics Research Center, Stanford, CA (September 2003) [Poster].

S. E. Harris, "*Single Cycle Optical Pulses*," Prism Inaugural Symposium, Princeton University, New Jersey (October 2003) [Invited].

D. R. Walker, M. Y. Shverdin, D. D. Yavuz, G. Y. Yin and S. E. Harris, "*Ultrashort Optical Pulse Generation by Molecular Modulation*," Max Planck Institute for Quantum Optics, Garching, Germany (November 2003) [Invited].

S. E. Harris, "*Physics and Application of Slow Light*," DARPA Slow Light Workshop, Orlando, Florida (December 2003) [Invited].

S. E. Harris, "*Generation of Spontaneous Photons*," Stanford Quantum Entanglement Symposium, Stanford, California (December 2003) [Invited].

M. Shverdin, D. R. Walker, D. D. Yavuz, G. Y. Yin and S. E. Harris, "*Generation of a Single-Cycle Optical Pulse*," CLEO Conference, San Francisco, CA (May 2004) [Post Deadline].

S. E. Harris, "*Generation of Single-Cycle Optical Pulse*," ETH Physical Colloquium, Zurich, Switzerland (June 2004) [Invited].

D. R. Walker, M. Y. Shverdin, D. D. Yavuz, G. Y. Yin and S. E. Harris, "*Generation of a Single-Cycle Optical Pulse*," International Conference on Ultrafast Phenomena, Niigata, Japan (July 2004) [Invited].

D. R. Walker, M. Y. Shverdin, D. D. Yavuz, G. Y. Yin and S. E. Harris, "*Single-Cycle Optical Pulse Generation*," International Conference on University of Electro-Communications, Chofu, Tokyo, Japan (July 2004) [Invited].

M. Shverdin, D. R. Walker, D. D. Yavuz, G. Y. Yin and S. E. Harris, "*Generation of a Single-Cycle Optical Pulse*," Nonlinear Optics Topical Meeting, Waikoloa, Hawaii (August 2004) [Invited].

M. Y. Shverdin, D. R. Walker, D. D. Yavuz, S. Goda, G. Y. Yin and S. E. Harris, "*Single-Cycle Optical Pulse Shaping*," Stanford Photonics Research Center, Stanford, CA (September 2004) [Poster].

VI. List of Participating Scientific Personnel

Faculty: Harris, S. E.

Graduate Students: Goda, Sunil
Walker, David (Ph.D. awarded)

Graduate Students (FTE): Braje, Danielle (Ph.D. awarded)

Other Scientific Staff: Yin, G. Y.

VII. Report of Inventions

None

VIII. Bibliography of Principal Investigator

See publication list

This work has been jointly supported by the Air Force Office of Scientific Research, the Air Force Research Laboratory, the Army Research Office, and the Multidisciplinary Research Initiative Program.

List of Appendixes

1. Abstract page of paper titled, "*Spatial Raman Solitons*".
2. Abstract page of paper titled, "*A Quasiperiodic Approach to Ultrashort Pulses*".
3. Abstract page of paper titled, "*Low-Light-Level Nonlinear Optics with Slow Light*".
4. Abstract page of paper titled, "*Quasiperiodic Raman Technique for Ultrashort Pulse Generation*".
5. Abstract page of paper titled, "*Elimination of Feshbach Loss in a Bose-Einstein Condensate*".
6. Abstract page of paper titled, "*(2+1)-Dimensional Stable Spatial Raman Solitons*".
7. Abstract page of paper titled, "*Generation and Control of Femtosecond Pulses by Molecular Modulation*".
8. Abstract page of paper titled, "*Generation of a Single-Cycle Optical Pulse*".

Spatial Raman solitons

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(Received 20 December 2002; published 22 April 2003)

We predict multifrequency spatial soliton propagation in a strongly driven Raman medium. The essential idea is the adiabatic preparation of a near-maximum molecular coherence.

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PACS number(s): 42.50.Gy, 32.80.Qk, 42.65.Dr, 42.65.Tg

It has been recently demonstrated [1–3] how adiabatically prepared molecules can generate a collinearly propagating comb of Raman sidebands with many octaves of spectral bandwidth. This is achieved by driving a Raman medium with two linearly polarized, single-mode laser fields whose frequency difference is slightly detuned from the Raman resonance. When the intensities of the two driving lasers are sufficiently large, the magnitude of the coherence of the Raman transition approaches its maximum value $|\rho_{ab}| \approx 0.5$. The generation and the phase slip lengths become comparable, and a very broad collinear spectrum is produced with phase-matching playing a negligible role. We have demonstrated the generation of vibrational and rotational Raman spectra covering the infrared, visible, and ultraviolet regions, in molecular deuterium (D_2) and hydrogen (H_2) [2,3]. In related work, Hakuta and co-workers have reported the generation of a comb of vibrational sidebands in solid H_2 , and rovibrational sidebands in a liquid hydrogen droplet [4–6].

When the two driving lasers are opposite circularly polarized, conservation of angular momentum forbids the generation of additional sidebands [7]. Instead, the established molecular coherence modifies the refractive indices of the driving frequencies [8,9]. Noting Fig. 1, depending on the sign of the Raman detuning $\Delta\omega$, the molecular coherence ρ_{ab} is either in phase (phased state) or out of phase (antiphased state of the molecular system) with the strong two-photon drive. The refractive indices of the driving frequencies are then either enhanced (phased) or reduced (antiphased) [9]. This variation in the refractive index can cause self-focusing or self-defocusing of the driving lasers, significantly altering beam diffraction. We have recently observed this effect, producing a change of $\approx 50\%$ in beam size by controlling the phase of coherently rotating H_2 molecules [10].

In this paper, for the first time to our knowledge, we demonstrate the existence of spatial solitons in such a strongly driven Raman system. We show that two driving lasers with specific spatial profiles will drive the Raman coherence such that the effects of diffraction will be exactly canceled by Raman self-focusing (bright soliton) or self-defocusing (dark soliton).

In pertinent prior work, spatial solitons have been observed in many different systems including three-frequency solitons in media with second-order nonlinearity [11,12]. Several authors have predicted formation of multifrequency spatial solitons in media with self- and cross-phase modulations [13]. There is an extensive literature on temporal Raman solitons [14,15]. In particular, Kaplan and Shkolnikov

have demonstrated a comb of Raman sidebands with an effective 2π area that propagates without change in their temporal shape in a self-induced transparencylike manner. Combining the concepts of spatial and temporal solitons has produced the idea of light bullets, a simultaneous self-trapping in space and time [16]. The work presented in this paper can be considered as the spatial analog of recently predicted EIT-like (electromagnetically induced transparency) Raman eigenvectors where the Raman nonlinearity was used to exactly compensate for the dispersion [17].

We begin by developing the formalism for a model molecular system interacting with two opposite circularly polarized driving lasers (termed the pump and the Stokes). Noting Fig. 1, we consider two-dimensional propagation (one transverse dimension) of the driving lasers with electric-field envelopes $E_p(x, z, t)$ and $E_s(x, z, t)$ such that the total field is $\vec{E}(x, z, t) = \text{Re}\{(E_p(x, z, t)\exp[j(\omega_p t - k_p z)] + E_s(x, z, t)\exp[j(\omega_s t - k_s z)])\}$. The coherence (off-diagonal density-matrix element) of the Raman transition is $\hat{\rho}_{ab}(x, z, t) = \text{Re}\{\rho_{ab}(x, z, t)\exp[j((\omega_p - \omega_s)t - (k_p - k_s)z)]\}$. $\Delta\omega$ is the two-photon detuning from the Raman resonance $\Delta\omega = (\omega_b - \omega_a) - (\omega_p - \omega_s)$; $k_p = \omega_p/c$ and $k_s = \omega_s/c$. When the detunings from one-photon resonances are large and for the ideal case of zero linewidth of the Raman transition, the temporal evolution of the probability amplitudes of Raman states $|a\rangle$ and $|b\rangle$ is described by the following effective Hamiltonian [1,9]:

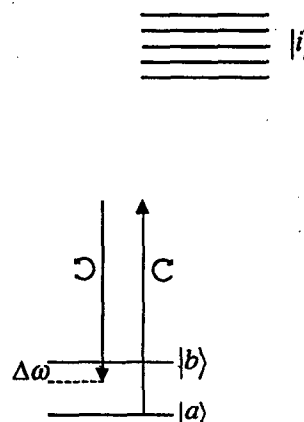


FIG. 1. Energy-level schematic showing the interaction of the two driving lasers with the molecular states. In the configuration shown, the two-photon detuning $\Delta\omega$ is positive (phased eigenstate), as required for bright soliton formation.

Low-light-level nonlinear optics with slow light

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 (Received 25 April 2003; published 15 October 2003)

Electromagnetically induced transparency in an optically thick, cold medium creates a unique system where pulse-propagation velocities may be orders of magnitude less than c and optical nonlinearities become exceedingly large. As a result, nonlinear processes may be efficient at low-light levels. Using an atomic system with three, independent channels, we demonstrate a quantum interference switch where a laser pulse with an energy per area of ~ 23 photons per $\lambda^2/(2\pi)$ causes a $1/e$ absorption of a second pulse.

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PACS number(s): 42.50.Gy, 32.80.Pj, 42.65.An

Interacting single photons, perhaps in an entangled state, are ideal candidates for applications in quantum information processing [1]. Because the strength of the interaction of single light quanta is typically weak, conventional nonlinear optics requires powerful laser beams focused tightly in nonlinear materials. When electromagnetically induced transparency (EIT) [2] is established in an optically thick medium with narrow resonance linewidths [3], a light pulse may experience exceedingly large nonlinearities, and nonlinear optical processes may become efficient at energy densities as low as a photon per atomic cross section [4]. Low-light-level nonlinear optics has been of recent interest in the context of resonant four-wave mixing [5], teleportation of atomic ensembles [6,7], production of correlated photon states [8], and quantum computation [9]. Ultimately, one may envision a waveguide geometry of an area $\sim \lambda^2/(2\pi)$ where a photon interacts with another photon by shifting its phase, by causing it to be absorbed, or by generating a third photon. Because the peak power of an individual photon may be varied by changing its bandwidth, the figure of merit for low-light-level nonlinear optical processes, as used here, is energy per area rather than power per area.

This paper focuses on an EIT-based, two-photon absorptive process suggested by Harris and Yamamoto [10] and observed by Zhu and co-workers [11]. Conceptually, this effect is the absorptive analog of the giant Kerr effect [12]. We report the demonstration of switching in an optically thick regime where a pulse with energy per area of ~ 23 photons per $\lambda^2/(2\pi)$ causes a $1/e$ absorption of a second pulse.

The lower portion of Fig. 1 shows both the prototype (lower left) and actual (lower right) atomic system used in the experiment. The coupling laser, tuned to the $|2\rangle \rightarrow |3\rangle$ transition with Rabi frequency $\Omega_c = \mu_{23}E/\hbar$, creates a quantum interference which cancels the absorption and dispersion of the probe laser. Consequently, a probe laser of angular frequency ω_p has a slow group velocity and no absorption in the EIT medium [2]. The magnitude of the coupling laser and the optical depth of the medium determine both the allowable, EIT bandwidth and the group velocity of the probe beam. When a switching laser of angular frequency ω_s is applied, a second path is opened and simultaneous absorption of a probe and switching photon occurs.

In the actual atomic system, the three m_F states of the $5S_{1/2}(F=1)$ ground level are populated. With the polarizations as depicted in Fig. 1, there are three, parallel and independent channels, each of which contributes to the total susceptibility.

In the following paragraphs, we compare the experimental results with calculated quantities. The calculation includes dephasing and extends the results of Harris and Yamamoto [10] to the three, parallel channels of Fig. 1. We take the magnitude of the probe-laser Rabi frequency $|\Omega_p^{(i)}|$ to be sufficiently small as compared to the coupling laser Rabi frequency $|\Omega_c^{(i)}|$ so that the atomic population remains almost completely in the level $|1\rangle$. The susceptibility at the probe frequency of the multistate system is

$$\chi = \sum_{i=1}^3 \frac{\mathcal{N}^{(i)} |\mu_{13}^{(i)}|^2}{\hbar \epsilon_0} \times \left[\frac{|\Omega_s^{(i)}|^2 - 4\Delta\tilde{\omega}_s\Delta\tilde{\omega}_c}{4\Delta\tilde{\omega}_p\Delta\tilde{\omega}_c\Delta\tilde{\omega}_s - |\Omega_c^{(i)}|^2\Delta\tilde{\omega}_s - |\Omega_s^{(i)}|^2\Delta\tilde{\omega}_p} \right]. \quad (1)$$

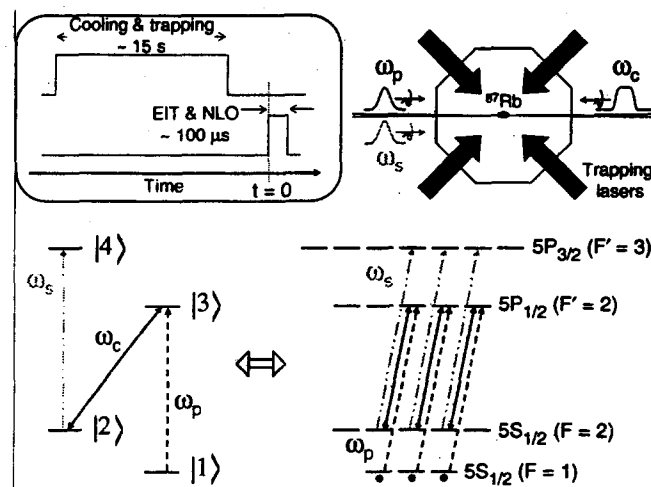


FIG. 1. (Color online) The experiment is performed in a 100- μ s window 50 μ s after shutting off the magnetic field and trapping lasers. The upper right corner depicts the laser beam orientations and polarizations. The lower left shows the prototype, four-level system; the lower right is the actual ^{87}Rb system used in the experiment.

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Quasiperiodic Raman Technique for Ultrashort Pulse Generation

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(Received 6 June 2003; published 3 December 2003)

We report the experimental demonstration of a new Raman technique that produces 200 sidebands, ranging in wavelength from 3 μm to 195 nm. By studying multiphoton ionization of nitric oxide (NO) molecules, we show mutual phase coherence among 15 visible sidebands covering 0.63 octaves of bandwidth.

DOI: 10.1103/PhysRevLett.91.233602

PACS numbers: 42.50.Gy, 32.80.Qk, 42.65.Dr, 42.65.Re

A new approach for generating ultrashort pulses of radiation utilizes coherently oscillating molecules [1,2]. Two laser fields, whose frequency difference is slightly detuned from a Raman resonance, will prepare the molecules in a superposition of states $|g\rangle$ and $|e\rangle$ (Fig. 1). When the intensities of the two driving lasers are sufficiently large, the magnitude of the coherence of the Raman transition approaches its maximum value, $|\rho_{ge}| = 0.5$. Such a coherently vibrating ensemble of molecules acts as a local oscillator and modulates the driving lasers, producing collinear sidebands spanning over four octaves of bandwidth. Recent experiments have demonstrated the generation of vibrational and rotational Raman spectra covering the infrared, visible, and ultraviolet spectral regions in molecular deuterium (D_2), hydrogen (H_2), and solid H_2 . Sokolov and colleagues have shown phase coherence among five vibrational Raman sidebands and demonstrated the generation of a near-single-cycle pulse structure [3]. Two limitations of this Raman technique are (i) the generated number of sidebands is low, limiting the number of terms of the Fourier series available for temporal pulse shaping, and (ii) the synthesized time waveform is a periodic train of pulses with a pulse spacing which is determined by the Raman transition frequency. As an example, in D_2 , the $\nu'' = 0 \rightarrow \nu' = 1$ vibrational transition is 2994 cm^{-1} and the time between pulses is 11 fs.

In this Letter we demonstrate a quasiperiodic Raman technique that overcomes these limitations [4]. Noting Fig. 1, we drive two Raman resonances with different oscillation frequencies and produce 200 sidebands with frequencies of the form

$$\omega_{q,r} = \omega_0 + q\omega_a + r\omega_b, \quad (1)$$

where q and r are integers and ω_a and ω_b are the frequencies of the respective Raman transitions. We demonstrate phase coherence among 15 sidebands by studying multiphoton ionization of nitric oxide (NO) molecules. In general, the ratio of the two transition frequencies, ω_a/ω_b , is irrational. As a result, the double Fourier series of Eq. (1) synthesizes a quasiperiodic time waveform $E(t)$. Formally, quasiperiodicity means that, for every $\epsilon > 0$, there exists a τ_ϵ such that [5]

$$|E(t) - E(t - \tau_\epsilon)| < \epsilon, \quad (2)$$

for all t . The key advantage of the quasiperiodic technique is that the number of sidebands that is produced is equal to the product of the number of sidebands generated by each Raman excitation alone. If the respective cells produce N_a and N_b sidebands, then the two cells in series produce a total of $N_a N_b$ sidebands with a bandwidth of $N_a \omega_a + N_b \omega_b$. By adjusting the phases of the respective Fourier components of this spectrum, we may obtain a waveform with a prescribed temporal shape. This waveform is quasiperiodic; i.e., at seemingly random times, the prescribed pulse comes close to replicating itself. These replications occur with an average periodicity of [4]

$$T = (2\pi) \frac{N_a N_b}{N_a \omega_a + N_b \omega_b}. \quad (3)$$

This average periodicity may be made quite large. For example, if $\omega_a \approx \omega_b$ and $N_a \approx N_b$, $T \approx \pi N_a / \omega_a$. For $N_a = N_b = 30$ and $\omega_a \approx \omega_b = 500 \text{ cm}^{-1}$, the average periodicity is 1 ps. Mode locking such a spectrum would produce pulses with a maximum peak power enhancement of about 900. This waveform will have pulses within 80% of maximum enhancement on average once every several picoseconds with smaller amplitude pulses occurring more frequently.

We cite related earlier work: The idea of using a Raman spectrum for synthesizing ultrashort pulses was

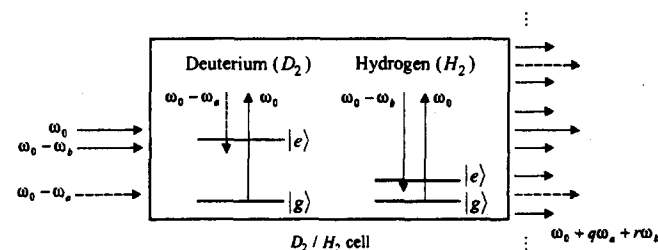


FIG. 1. Schematic of successive molecular modulators. A pair of lasers drives coherent vibrations in molecular D_2 , whereas another pair drives coherent rotations in H_2 . The frequency difference of the driving lasers is slightly detuned from the Raman resonance so as to adiabatically prepare the molecules in a superposition state.



Elimination of Feshbach loss in a Bose–Einstein condensate

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Received 23 January 2003; received in revised form 14 July 2003; accepted 10 February 2004

Abstract

We suggest a technique to eliminate inelastic losses in an atomic condensate when tuned close to a Feshbach resonance. The key idea is to couple the quasi-bound molecular state to a bound molecular state with an electromagnetic field. Such coupling forces the population of the Feshbach state to zero, thereby eliminating all of the losses associated with this state.

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In recent experiments on Bose–Einstein condensates large loss rates were observed when a quasi-bound molecular state was tuned slowly close to a Feshbach resonance with an atomic condensate [1,2]. Although the precise mechanism for this loss is not understood, it is likely that the loss is associated with the population of the quasi-bound molecular state. As suggested by Yurovsky et al. [3], one mechanism which causes loss is three body recombination.

In this work we extend the suggestion of Harris [4] to coupled, zero-temperature, atomic and molecular condensates, and demonstrate a technique to eliminate Feshbach loss. The key idea is to

couple the quasi-bound molecular state to a bound molecular state with an electromagnetic field. Due to destructive interference, the quasi-bound molecular state accumulates no population and all of the losses associated with this state are eliminated. The nature of this interference has strong similarities with electromagnetically induced transparency (EIT) for light fields, where an incident optical beam tuned to what was previously line center has near zero absorption [5].

A schematic of the system to be studied is shown in Fig. 1. The energy of the atomic condensate is magnetically tuned close to a Feshbach resonance with the quasi-bound diatomic molecules. We assume that the quasi-bound molecules decay with a rate Γ_1 . The quantity Ω in Fig. 1 is the Rabi frequency of the electromagnetic field that couples the quasi-bound and bound molecular states. In symmetric molecules this transition is dipole forbidden and Ω is the effective two-photon

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(2+1)-dimensional stable spatial Raman solitons

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We analyze the formation, propagation, and interaction of stable two-frequency (2+1)-dimensional solitons, formed in a Raman media driven near maximum molecular coherence. The propagating light is trapped in the two transverse dimensions.

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The generation of stable spatial optical solitons is of great interest due to the variety of the solitons' interactions, their particlelike characteristics, and their potential technological applications [1]. Spatial soliton formation requires a balance between the beam's tendencies to self-focus and diffract. In bulk [three-dimensional (3D)] media, such propagation is unstable, unless the focusing nonlinearity saturates with the intensity [2,3]. Experimentally, spatial (2+1)-dimensional solitons have been demonstrated in a variety of physical systems, including photorefractive media [4,5], quadratic media [6,7], and saturable Kerr media [8,9]. While the equations governing the various types of self-trapped waves differ, the fundamental propagation and interaction properties remain the same [10].

We have recently proposed a method for generating spatial Raman solitons [11]. We adiabatically prepare a Raman transition in a single eigenstate near maximum molecular coherence by driving the medium with two opposite circularly polarized laser fields whose frequency difference is slightly detuned from the Raman resonance (Fig. 1). Depending on the sign of the detuning $\Delta\omega$, the adiabatically established molecular coherence is either in phase or out of phase with the strong two-photon drive. Angular-momentum conservation rules prevent Stokes and anti-Stokes sideband generation [12]. Instead the molecular coherence modifies the refractive indices of the driving lasers [13–15] and leads to either focusing or defocusing, depending on the sign on the detuning [16]. An appropriate choice of the input intensities and the two-photon detuning from the Raman resonance leads to bright ($\Delta\omega > 0$) or dark ($\Delta\omega < 0$) soliton formation.

In this paper, we extend the analysis of bright Raman solitons to three spatial dimensions. We numerically and theoretically demonstrate that these solitary waves are stable to perturbations and survive soliton-soliton collisions. Stability is achieved by operating near maximum molecular coherence, $|\rho_{ab}| \approx 1/2$, and thereby saturating the Raman nonlinearity with the laser intensity. Adiabatic preparation of near maximum coherence is essential and ties this work to broadband Raman generation [17] and electromagnetically induced transparency [18].

Following Ref. [19], we consider a model Raman system excited with opposite circularly polarized pump, E_p , and Stokes, E_s , lasers, oscillating at frequencies ω_p and ω_s . The analysis applies to beams propagating along the z axis with the electric field oscillating in two transverse dimensions (x

and y). We assume no time variation in the propagating beam profiles. Experimentally, this can be realized using flat-top pulses. The slowly varying envelope propagation equations for the pump and the Stokes beams at steady state are

$$2k_p \frac{\partial E_p}{\partial z} + j \left(\frac{\partial^2 E_p}{\partial x^2} + \frac{\partial^2 E_p}{\partial y^2} \right) = -j2\eta\hbar\omega_p k_p N (a_p \rho_{aa} E_p + d_p \rho_{bb} E_p + b^* \rho_{ab} E_s),$$

$$2k_s \frac{\partial E_s}{\partial z} + j \left(\frac{\partial^2 E_s}{\partial x^2} + \frac{\partial^2 E_s}{\partial y^2} \right) = -j2\eta\hbar\omega_s k_s N (a_s \rho_{aa} E_s + d_s \rho_{bb} E_s + b \rho_{ab}^* E_p), \quad (1)$$

where N is the molecule number density and $\eta = (\mu/\epsilon_0)^{1/2}$. The population in the two states $|a\rangle$ and $|b\rangle$ are given by ρ_{aa} and ρ_{bb} . The molecular coherence of the two levels, ρ_{ab} (off-diagonal density-matrix element), is responsible for the intensity dependence of the refractive index. The dispersion coefficients at the pump and the Stokes frequencies, a_p , a_s , d_p , d_s , and the coupling coefficient b , are calculated elsewhere [19]. When the matrix elements of the Hamiltonian that describes the evolution of the molecular system vary slowly compared to the separation of the eigenvalues of the

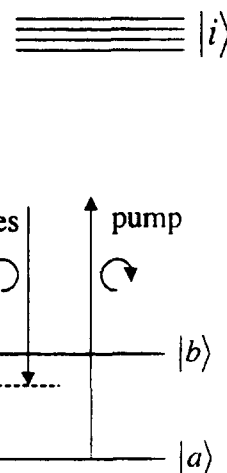


FIG. 1. Energy-level diagram of a sample Raman system driven by two opposite circular polarized fields. As shown, the two-photon detuning is positive leading to self-focusing.

Generation and Control of Femtosecond Pulses by Molecular Modulation

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We have demonstrated that coherent molecular modulation can result in the collinear generation of mutually-coherent spectral sidebands that extend in frequency from the infrared to the far ultraviolet. Our technique is based on adiabatic preparation of a highly coherent molecular superposition-state, which is achieved by using narrow-linewidth lasers slightly detuned from a Raman resonance. The phases of the resultant Stokes and anti-Stokes sidebands are adjusted in order to synthesize desired single-cycle pulse trains at the target. In this article we review recent improvements and developments in this area, including: techniques for increasing the number of generated sidebands; synchronization of the pulse trains with the molecular motion in the given molecular system; laser self-focusing and spatial soliton formation due to the coherent interaction of light with oscillating molecules. In the future, this Raman source may produce sub-cycle optical pulses, and allow synthesis of waveforms where the electric field is a predetermined function of time, not limited to a quasi-sinusoidal oscillation.

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Introduction

The important role of electronic pulse shaping in the microwave and radio frequency regions of the spectrum is well known. Over the last several years we have developed techniques, which allow pulse shaping in the optical and ultraviolet portions of the electromagnetic spectrum. In particular, we have made a light source that has almost four octaves of optical bandwidth and extends from 3 μm in the near-infrared to at least 195 nm in the ultraviolet. In recent experiments we have used both manual and electronic techniques to control the phases of a small subset of these sidebands and to thereby make femtosecond pulses with a desired pulse shape.

The prototype system for generating a broad coherent spectrum is shown in fig. 1. We apply two lasers, in this case Nd:YAG and Ti:Sapphire, whose frequency difference is equal to the fundamental vibrational frequency of molecular deuterium. As explained further below, it is important that

Generation of a Single-Cycle Optical Pulse

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Abstract

We make use of coherent control of four-wave-mixing to the ultraviolet as a diagnostic and describe the generation of a periodic optical waveform where the spectrum is sufficiently broad that the envelope is approximately a single cycle in length, and where the temporal shape of this envelope may be synthesized by varying the coefficients of a Fourier series. Specifically, using seven sidebands, we report the generation of a train of single-cycle optical pulses with a pulsewidth of 1.6 fs, a pulse separation of 11 fs, and a peak power of 1 MW.

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