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13. ABSTRACT (Maximum 200 words)

The final report describes progress in the use of electromagnetically induced transparency for the realization of new types of nonlinear interactions and processes. We have worked in two areas: (1) The generation of femtosecond pulses by phased and anti-phased molecular states and the use of this radiation for new types of physical processes, and (2) The demonstration of elementary nonlinear optical processes at low-light-levels. Highlights of the work on this program include the suggestion and first demonstration of the use of an EIT-like Raman process to produce a spectrum with a width over 50,000 cm-1 of bandwidth, and the compression of this radiation to pulses of several femtoseconds in length. By using a technique, which we call multiplicative, we are able to obtain over 200 sidebands. In the future this should allow the synthesis of sub-cycle waveforms of arbitrary shape. In other work under this contract, we have observed an efficient nonlinear optical process at an energy of several pJ.

14. SUBJECT TERMS
Electromagnetically induced transparency, EIT-like Raman process, femtosecond pulse generation, Raman technique for single-cycle pulse generation, nonlinear optical optics with cold atoms, nonlinear optical processes at low light levels, slow light.

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RESEARCH STUDIES ON
ELECTROMAGNETICALLY INDUCED TRANSPARENCY

FINAL PROGRESS REPORT

(1 FEBRUARY 2001 – 31 JANUARY 2004)

S. E. HARRIS

U.S. ARMY RESEARCH OFFICE

GRANT DAAD19-01-1-0028

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April 2004

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Table of Contents

I. Statement of the 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.

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).

III. Peer-Reviewed Publication List

S. E. Harris, A. V. Sokolov, D. R. Walker, D. D. Yavuz, and G. Y. Yin, "Collinear Light Scattering Using Electromagnetically Induced Transparency," in *Atomic Physics 17*, edited by E. Arimondo, P. DeNatale, and M. Inguscio (American Institute of Physics, New York, 2001), pp. 189-203.

A. V. Sokolov, D. D. Yavuz, D. R. Walker, G. Y. Yin, and S. E. Harris, "Light Modulation at Molecular Frequencies," *Phys. Rev. A* **63**, 05801/1-05801/3 (April 2001).

A. V. Sokolov, S. J. Sharpe, M. Shverdin, D. R. Walker, D. D. Yavuz, G. Y. Yin, and S. E. Harris, "Optical Frequency Conversion by a Rotating Molecular Waveplate," *Opt. Lett.* **26**, 728-730 (May 2001).

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).

S. E. Harris, A. V. Sokolov, D. R. Walker, D. D. Yavuz, and G. Y. Yin, "Raman Technique for Femtosecond Pulse Generation," in *Laser Physics at the Limit*, edited by H. Figger, D. Meschede, and C. Zimmermann (Springer-Verlag, New York, 2002), pp. 355-365.

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).

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).

S. E. Harris, "Control of Feshbach Resonances by Quantum Interference," *Phys. Rev. A* **66**, 010701-1/010701-4 (July 2002).

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).

A. V. Sokolov and S. E. Harris, "Ultrashort Pulse Generation by Molecular Modulation," *J. Opt. B: Quantum Semiclass. Opt.* **5**, R1-R26 (December 2002).

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

"*Slow Light,*" Stanford Photonics Research Center (SPRC) Annual Meeting, Stanford University, Stanford, California (September 2001) [Keynote Speaker].

D. Walker, S. E. Harris, "Coherant Control of Multiphoton Ionization," Optical Society of America Annual Meeting, Long Beach, California (October 2001).

D. D. Yavuz, S. E. Harris, "Spatial Solitons," Optical Society of America Annual Meeting, Long Beach, California (October 2001).

"*Nonlinear Optics at Low Light Levels*", OSD University Research Program Review, Baltimore, MD (November 2001) [Invited].

"*Electromagnetically Induced Transparency and Its Application to Slow Light,*" 2002 American Association for the Advancement of Science Annual Meeting, Boston, Massachusetts (February 2002) [Invited].

"*Quasi-Periodic Functions and Femtosecond Pulses,*" CLEO/QELS 2002, Long Beach, California (May 2002) [Invited].

"*Quasi-Periodic Functions and Femtosecond Pulses,*" Nonlinear Optics Conference 2002, Maui, Hawaii (July 2002) [Invited].

"*Electromagnetically Induced Transparency with Matter Waves,*" Fano Memorial Symposium, Boston, Massachusettes (July 2002) [Invited].

D. D. Yavuz, S. E. Harris, "Elimination of Feshbach loss for a Bose-Einstein Condensate," International Conference on Atomic Physics, Boston, Massachusettes (July 2002) [Poster].

D. Walker, S. E. Harris, "Quasi-Periodic Functions and Femtosecond Pulses," Nonlinear Optics Conference, Maui, Hawaii (July 2002) [Poster].

"Electromagnetically Induced Transparency with Matter Waves," Atomic and Molecular Physics Seminar, Berkeley, California (September 2002) [Invited].

"Electromagnetically Induced Tranparency with Light Waves and Matter Waves," Optical Society of America Annual Meeting, Orlando, Florida (September 2002) [Invited].

"Slow Light, Giant Nonlinearities: Low-Light-Level Nonlinear Optics in Cold Atoms," MURI Meeting, Boulder, Colorado (November 2002) [Invited].

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

“Single Cycle Optical Pulses,” Agilent Labs, Palo Alto (May 2003) [Invited].

“Quasi-Periodic Raman Technique,” Grand Targee Quantum Electronics Meeting, Wyoming (July 2003) [Invited].

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

“Photon Switching with Slow Light: Low-Light-Level Nonlinear Optics in Cold Atoms,” Gordon Research Conference, Mount Holyoke College, Massachusetts (August 2003) [Invited].

“Quasiperiodic Raman Technique For Ultrashort Pulse Generation,” International conference on laser physics, Hamburg, Germany (August 2003) [Invited].

“Nonlinear Optics with Slow Light,” Gordon Conference on Quantum Control of Light and Matter, South Hadley, MA (August 2003) [Invited].

D. Yavuz, 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].

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

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

V. List of Participating Scientific Personnel

Harris, S. E.	Principal Investigator
Yin, G. Y.	Senior Researcher Scientist
Alexei Sokolov	Ph.D. earned during the grant period
Scott Sharpe	Ph.D. earned during the grant period
Deniz Yavuz	Ph.D. earned during the grant period
Vlatko Balic	
Pavel Kolchin	
Miroslav Shverdin	
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VI. Relation to Other Contracts

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