

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

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1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE April 1994	3. REPORT TYPE AND DATES COVERED FINAL REPORT 15 Dec 91- 14 Oct 94
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4. TITLE AND SUBTITLE "Research Studies in Electromagnetically Induced Transparency"	61102 2583/00
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9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) AFOSR/NE 110 Duncan Avenue Suite B115 Bolling AFB DC 20332-0001	10. SPONSORING / MONITORING AGENCY REPORT NUMBER F49620-92-J-0066
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11. SUPPLEMENTARY NOTES
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12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution unlimited.	12b. DISTRIBUTION CODE
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13. ABSTRACT (Maximum 200 words)
To make an atom transparent at a given laser frequency, one applies a second laser whose frequency is equal to the difference of an otherwise empty state and the point in frequency space to which a probing laser is tuned. This type of transparency exhibits an essential nonreciprocity where, though absorption and refractive index may be negated, the nonlinear susceptibilities and coefficients for stimulated and spontaneous remain unchanged. We believe that there may be a new regime of nonlinear optics with special properties as resonances are approached.

DTIC QUALITY INSPECTED 8

14. SUBJECT TERMS Electromagnetically Induced Transparency	15. NUMBER OF PAGES
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT UNCLASSIFIED	18. SECURITY CLASSIFICATION OF THIS PAGE UNCLASSIFIED	19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED	20. LIMITATION OF ABSTRACT UL
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**Edward L. Ginzton Laboratory
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**"RESEARCH STUDIES IN
ELECTROMAGNETICALLY INDUCED TRANSPARENCY"**

Final
~~ANNUAL~~ TECHNICAL REPORT

**FOR
THE AIR FORCE OFFICE OF SCIENTIFIC RESEARCH
AND
THE ARMY RESEARCH OFFICE**

Contract F49620-92-J-0066

For the Period

15 October 1992 - 14 October 1993

Principal Investigator:

S. E. Harris

April 1994

I. INTRODUCTION

Our work is now centered in two major areas. The first is that of electromagnetically induced transparency and lasers without inversion.

During this previous year we have been in a building phase. On both sides of our program, new laser systems with unique specifications have been developed. This work is almost complete. On the transparency side of the program we now have running temporally synchronized Ti:Sapphire lasers with a frequency stability of about 5 MHz. On the short wavelength side of the program we have what may be the highest peak power system operating anywhere. This system was built under Professor Barty's direction and has a peak power in excess of 10^{12} W with a pulse length of under 30 fs.

We are now poised for two key experiments. Brian Lemoff will soon attempt to produce lasers which operate in the 30-50 nm spectral region. (I view the odds on this experiment as about 50-50. There are many uncertainties.) Trey Gordon will attempt to show an exposure reduction of a factor of seven by using time-gated x-rays. Athos Kasapi and Maneesh Jain will attempt a variety of new types of transparency and nonlinear optical experiments.

In Section II of this report we summarize the contributions made during the overall contract period. In Section III we list publications which acknowledge this contract. Appendix A gives the abstracts of each of these publications.

Before proceeding we note that the work described here has been, and will continue to be, jointly supported by other agencies; primarily the Office of Naval Research, the Army Research Office, and the Strategic Defense Initiative Organization.

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II. SUMMARY OF ACCOMPLISHMENTS

- (1) A particularly exciting development during this contract period was the first demonstration of the use of femtosecond time scale lasers to create incoherent x-rays which extend beyond 1 MeV. We have found an energy conversion efficiency from laser energy to x-ray energy above 20 keV of about 0.3%.
- (2) We have completed and published studies of the 96.9 nm laser in neutral Cs. This was the first laser to operate with its upper level above the continuum.
- (3) We have completed an effort to generate very high-order harmonics using the ultra-high-power femtosecond system which was also used to produce the incoherent x-rays. As an outgrowth of this work we have noted the possibility that these high-order harmonics, to the extent that they are appropriately phased, will produce temporal structure under radiation on the order of 5×10^{-17} sec.
- (4) We have made several improvements and developments toward the realization of a new Ti:Sapphire based femtosecond laser system. A new oscillator has been constructed which produces 804 nm pulses with durations as short as 20 fs and with peak powers as high as 500 kW. At the time of construction, these results represented the shortest duration pulses ever generated directly from a laser oscillator. Modeling of the dispersive intracavity components allows minimization of higher-order intracavity phase distortion. A high-modulation-depth,

acousto-optic modulator allows intracavity power, self-phase modulation, and pulse bandwidth to be maximized without concurrent cw operation. Ray tracing of the laser resonator also reveals that cubic phase distortion can be eliminated in a laser resonator by the correct choice of prism material and operating wavelength. This suggests the possibility of the construction of significantly shorter duration laser oscillators.

- (5) We have first results which show the highly-dispersive properties of electromagnetically induced transparency. Tentatively, we observe a group velocity reduction, as compared to the speed of light, of greater than a factor of 100.
- (6) We have proposed a technique for using an intense femtosecond laser to directly excite XUV lasers. Tunneling ionization by circularly-polarized radiation produces both the ions and hot electrons which are necessary to excite the upper laser level. The systems should work in the 30-50 nm spectral region.
- (7) During this year we have reported the first demonstration of electromagnetically induced phasematching in collisionally broadened Pb vapor. At a critical intensity at which the Rabi frequency of a dressing 1064 nm laser overcomes the Doppler broadening of the vapor, the generated four-frequency mixing signal at 283 nm increased in a step-like manner by a factor of 59.

III. PUBLICATIONS

1. C. P. J. Barty, G. Y. Yin, J. E. Field, D. A. King, K. H. Hahn, J. F. Young, and S. E. Harris, "Studies of a 96.9-nm Laser in Neutral Cesium," *Phys. Rev. A* **46**, 4286-4296 (October 1992).
2. J. D. Kmetec, "Ultrafast Laser Generation of Hard X-Rays," *IEEE J. Quantum Electron.* **QE-28**, 2382-2387 (October 1992).
3. B. E. Lemoff and C. P. J. Barty, "Generation of High Peak Power 20 fs Pulses from a Regeneratively Initiated, Self-Mode-Locked Ti:Sapphire Laser," *Opt. Lett.* **17**, 1357-1369 (October 1992).
4. S. J. Benerofe, G. Y. Yin, and S. E. Harris, "116 nm H₂ Laser Pumped by a Traveling-Wave Photoionization Electron Source," in *Vacuum Ultraviolet Radiation Physics*, edited by F. J. Wuilleumier, Y. Petroff, and I. Nenner (New Jersey, World Scientific, 1993), pp. 85-95.
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7. J. J. Macklin, J. D. Kmetec, and C. L. Gordon III, "High-Order Harmonic Generation Using Intense Femtosecond Pulses," *Phys. Rev. Lett.* **70**, 766-769 (February 1993).
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10. J. E. Field, "Vacuum-Rabi-Splitting-Induced Transparency," *Phys. Rev. A* **47**, 5064-5067 (June 1993).

11. S. E. Harris, J. J. Mäcklin, and T. W. Hänsch, "Atomic Scale Temporal Structure Inherent to High-Order Harmonic Generation," *Opt. Commun.* **100**, 487-490 (July 1993).
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13. B. E. Lemoff and C. P. J. Barty, "Quintic-Phase-Limited, Spatially Uniform Expansion and Recompression of Ultrashort Optical Pulses," *Opt. Lett.* **18**, 1651-1653 (October 1993).
14. C. P. J. Barty, C. L. Gordon III, B. E. Lemoff, P. T. Epp, and S. E. Harris, "Ultrashort Pulse Terawatt Lasers for the Generation of Coherent and Incoherent X-Ray Sources," in *Proceedings of Lasers '93*, (SUB),
15. C. P. J. Barty, B. E. Lemoff, C. K. Gordon III, and P. T. Epp, "Multiterawatt Amplification of Ultrabroadband Optical Pulses: Breaking the 100 fs Limit," in *Proceedings of OE/LASE '94*, (SUB),
16. C. P. J. Barty, C. L. Gordon III, J. D. Kmetec, B. E. Lemoff, and S. E. Harris, "Ultrashort High Peak Power Lasers and Generation of Hard Incoherent X-Rays," in *Proceedings of Lasers '92*, (SUB),
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