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1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
03 Oct 1996

3. REPORT TYPE AND DATES COVERED
Final Technical 01 Aug 93 - 31 Aug 96

4. TITLE AND SUBTITLE
Continuous Sources of Optical Coherence for Optical Processing

5. FUNDING NUMBERS
61103D
3484/TS

6. AUTHOR(S)
John E. Thomas

7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(ES)
DUKE UNIVERSITY
Department of Physics, Box 90305
Durham, NC 27708-0305

AFOSR-TR-96 0438

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AFOSR/NE
110 Duncan Avenue, Room B115
Bolling AFB, DC 20332-8080

10. SPONSORING / MONITORING AGENCY REPORT NUMBER
F49620-93-1-0448

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION / AVAILABILITY STATEMENT

APPROVED FOR PUBLIC RELEASE: DISTRIBUTION UNLIMITED

12 b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

A broad program to investigate the nonlinear optical properties of a new type of dense atomic medium has been undertaken. This medium consists of a dense, diverging supersonic atomic beam for which the Doppler broadening is nearly eliminated by means of a magnetic field gradient. Research has been focused on characterizing the coherent radiation of the medium when it is prepared by continuous spatially separated optical fields. Spatial, directional, and coherence properties of the coherent field, including its quantum noise, have been investigated.

DTIC QUALITY INSPECTED 3

19961016 079

14. SUBJECT TERMS
Optical coherence, photon echoes, optical noise, nonlinear optical processing, Wigner phase space distributions

15. NUMBER OF PAGES
10

16. PRICE CODE

17. SECURITY CLASSIFICATION OR REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

Enclosure 1

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18
298-102

Continuous Sources of Atomic Coherence for Optical Processing

J. E. Thomas

October 3, 1996

Physics Department, Duke University
Durham, North Carolina 27708-0305

FINAL REPORT FOR THE PERIOD 01 AUGUST, 1993–31 AUGUST, 1996.
Grant No. F49620-93-1-0448

Abstract

A broad program to investigate the nonlinear optical properties of a new type of dense atomic medium has been undertaken. This medium consists of a dense, diverging supersonic atomic beam for which the Doppler broadening is nearly eliminated by means of a magnetic field gradient. Research has focused on characterizing the coherent radiation of the medium when it is prepared by continuous spatially separated optical fields. Spatial, directional, and coherence properties of the coherent field, including its quantum noise, have been investigated.

Contents

1 Summary **3**

1.1 Continuous Spatial Photon Echoes 3

1.2 Optical Noise of Coherently Radiating Atoms 4

1.3 Optical Phase Space Imaging 5

1.4 Precision Position Measurement of Moving Atoms 6

2 References **7**

3 Publications **8**

4 Students Participating in this Research **9**

5 Patents and Inventions **9**

1 Summary

The primary goal of this research, which originated in the parent program (F19628-91-K-0018), has been the broad investigation of the optical physics of a new type of dense atomic medium, which was first demonstrated in the original program. To obtain large nonlinear optical signals in an atomic medium with a narrow spectral width, a dense sample of atoms is prepared in a novel way: An intense diverging supersonic atomic beam is used and the Doppler width is substantially reduced by using a magnetic field gradient along the laser propagation direction. For a supersonic beam there is approximately a one-to-one correspondence between the position at which an atom intersects a laser beam, and the Doppler shift. The magnetic field gradient essentially cancels the Doppler shifts by tuning the local atomic resonance frequency to match the Doppler shifted laser frequency. In this way, a dense atomic medium with a long 1-4 cm interaction path and a narrow 5-15 MHz linewidth is obtained. This is ideal for nonlinear optics applications. We call this system a magnetically compensated supersonic beam [1].

Based on magnetically compensated atomic beams, a method for generating continuous photon echoes [2] was developed in the parent program. These optical echoes are the continuous coherent radiation of an optically prepared, freely radiating sample of atoms in a magnetically compensated beam. These techniques have potential applications in nonlinear optical processing and in back action evading measurement of optical fields. The research undertaken in the present program has been focused on characterizing the spatial, directional, and coherence properties of the echo field, including its quantum noise. Results of these studies are described briefly in the following sections.

In addition to studying the optical characteristics of magnetically compensated beams, a number of interesting new directions for research emerged during the period of this program. These new directions are outgrowths of concepts in the original research plan, and also were pursued as part of the present program. These include the development of precision methods for position measurement of moving atoms, based on resonance imaging in magnetic and optical field gradients. Such methods will have important applications in the development of new techniques for neutral atom nanolithography and in fundamental experiments with ultracold atoms. Further, studies of the quantum noise properties of coherently radiating atoms in beams has lead to the development of sensitive new optical phase space imaging methods. These methods will have important applications in the tomography of random media, including biological imaging. Some results of these studies are described briefly below.

1.1 Continuous Spatial Photon Echoes

As described in our previous reports, the continuous photon echo method was developed in the parent program to explore new methods for nonlinear optical processing which can be implemented using echo techniques [2]. For example, spatial convolution and correlation integrals of optical field distributions can be done in real time by exciting the atomic beam with spatially separated optical fields and measuring the spatial distribution of the echo signal. The continuous echo method is based on a dense supersonic beam of samarium atoms, which forms a two-level atomic system.

Using this method, we have generated continuous spatial photon echoes by having the atoms in the beam traverse two continuous, spatially separated cw laser fields. This leads to a rephasing optical polarization downstream from the laser beams, which produces a spatial photon echo, analogous to that normally encountered in the time domain [2]. Research on continuous photon echoes formed the central topic of the Ph.D. disseration for Carl Schnurr.

We have used this system to study the spatial coherence of the echo and free induction decay signals. In the initial study, the echo field and the free induction decay field of the first excitation region were interfered to obtain interference fringes using Fourier optics methods. These fields were found to be mutually coherent and the interference pattern was shown to be interpretable as a new type of atom interferometer, based on collective radiaton from the atoms [3].

Particularly interesting were experiments on the the Fourier optics of continuous photon echoes. We showed that is is possible to measure the momentum distribution of the echo field with milli-photon momentum resolution by measuring the echo intensity in an appropriate Fourier plane. Further, we showed that the momentum distribution is determined by the slowly varying center of mass wavefunction of the coherently prepared atoms. This was demonstrated by modifying the atomic wavefunction using an optically generated potential and measuring the modified momentum distribution. This method has interesting potential applications in information storage and transmission via ground state atomic wavefunctions in atomic beams [4]. Recently, we have been exploring potential applications of this method that may provide new methods for quantum nondemolition measurement of optical field intensity via atomic interference.

1.2 Optical Noise of Coherently Radiating Atoms

The optical fields radiated by long lived atoms in a coherent superposition of atomic states have unique noise properties, which have not been extensively explored in previous work. The magnetically compensated beam method provides a unique means of exploring the noise properties of the radiation field of a dense atomic sample. Studies of phase-dependent noise in driven atomic samples will impact many areas of current research, for example electromagnetically induced transparency, where interference of multiple paths is used to cancel absorption, or laser cooling where atomic dipole fluctuations limit the ultimate temperature.

In order to explore the classical and quantum noise properties of the fields radiated by the atoms in a magnetically compensated beam, we have developed sensitive, new noise measurement methods which we believe will have wide applications beyond the current work. Two innovations have made these measurements possible, in addition to magnetically compensated supersonic beams. One is the method of subtracting signals from identically prepared atomic regions to measure quantum noise. This technique subtracts classical noise which is common to the two regions. However, since different atoms are excited in each region, the quantum noise is uncorrelated and adds. A second important feature of our experiments is the exploitation and optimization of well-known methods for measuring noise power spectra on a linear scale. This method is described in more detail in § 1.3.

These new noise measurement methods have allowed us to measure the complete phase-dependent noise spectrum of coherently prepared radiating atoms in our beam system. By offset locking the driving laser frequency, we have investigated atom noise spectra for both on- and off-resonant excitation. We use long-lived two level Yb atoms with a radiative lifetime of 1 μs, similar to our echo work. The noise spectra obtained in the experiments have been analyzed using a fluctuating Bloch vector picture, which provides a unified and physically appealing interpretation of the atomic sources of optical noise [5].

We have obtained recently exciting new noise spectra for off-resonant excitation. A remarkable result is that phase-dependent noise spectra for plus and minus 45° quadratures are found to be markedly different. A theoretical analysis shows that this is a pure quantum effect, traceable to vacuum fluctuations and time-ordering of the atomic operators. So far as we are aware this is the first time that the effects of time ordering have been shown to be directly manifested in an optical noise spectrum. We currently are writing a paper describing this research for submission to Physical Review Letters, and well as a longer review of this work for Physical Review A.

1.3 Optical Phase Space Imaging

In our noise measurement experiments, we developed a simple and effective method of measuring noise power spectra on a linear scale, with high dynamic range. We have recently demonstrated that this method can be extended to directly measure Wigner phase space (position-momentum) distributions for arbitrary optical fields. The importance of the new methods is that rigorous transport equations can be derived for Wigner distributions which include coherent and incoherent scattering contributions in a unified way. We expect that these methods will have wide applicability to studies of optical field propagation and to tomographic imaging by measuring the phase space distributions of reflected or transmitted optical fields. Further, they will be applicable to studies of light propagation in turbid media, for example atmospheric propagation or biological imaging, and also will provide important new methods of phase space imaging for general tomographic applications. These developments are described briefly below.

The basic method for measuring noise power spectra is based on an improvement of a method which is well known in light beating spectroscopy: We square the output of an analog spectrum analyzer using a low noise multiplier. The squared output of the multiplier is then sent to a lock-in amplifier, which subtracts the squared output with the light on and off. In this way, electronic noise is subtracted in real time and the lock-in output is proportional to the optical noise power spectrum. We have demonstrated this method by measuring the shot noise in a laser beam from several milliwatts down to two microwatts. The lock-in output scales linearly with laser power over four orders of magnitude. Further, the measured slope agrees with that calculated on the basis of shot noise and the system gain factors to within 10% [6].

This method works so well that we began exploring biological and atmospheric applications involving light propagation in diffusive media. We found that by heterodyning a signal field with a local oscillator, the Wigner phase space distribution for the signal field can be measured directly, and in real time. Briefly, this method works as follows.

We measure the heterodyne beat amplitude with a spectrum analyzer, and square the spectrum analyzer output as described above. The signal beam is chopped and the squarer output is synchronously detected with a lock-in amplifier. This subtracts electronic noise and the shot noise level of the local oscillator in real time. The lock-in output is proportional to the mean square beat signal.

A remarkable result which seems not to have been exploited previously is that the mean square beat signal is proportional to the overlap integral of the Wigner phase space distribution of the local oscillator with that of the signal field. The up shot is that the Wigner distribution of the signal field is measured with phase space resolution limited by the spatial extent and diffraction angle of the local oscillator (LO) beam. With a simple lens system, it is possible to scan the LO position and momentum, and obtain a contour plot of the mean square beat signal, which is just the smoothed Wigner distribution of the signal beam in transverse position and momentum. We have demonstrated the experimental measurement of Wigner distributions using this method [7]. We have also demonstrated a dynamic range of 13 orders of magnitude in a turbid medium for this method which may have important applications in biomedical imaging using optical lasers [8].

1.4 Precision Position Measurement of Moving Atoms

The use of magnetic field gradients in the compensated beam methods lead us to suggest that resonance imaging methods, based on magnetic as well as optically generated level shift gradients, may have important applications in the field of atom optics. We have shown both theoretically and experimentally that extremely high spatial resolution is attainable by such methods, and that uncertainty-principle-limited spatial resolution of better than 10 nm is achievable for moving atoms in beams and traps. Such methods have potential practical applications in neutral atom lithography and many fundamental applications in the precision measurement of ultra-cold atom position distributions and spatial correlation functions. These techniques are thoroughly discussed in our recent review paper [9].

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Continuous Photon Echoes in Magnetically Compensated Beams

1) C. Schnurr, T. Savard, L. J. Wang, and J. E. Thomas, "Detection of atomic interfernce via collective radiation," Opt. Lett. **20**, 413 (1995).

2) C. Schnurr, T. A. Savard, L. J. Wang, and J. E. Thomas, "Atomic wavefunction imaging via optical coherence," Phys. Rev. Lett. **74**, 1331 (1995).

Optical Noise in Magnetically Compensated Beams

3) L. J. Wang, A. M. Bacon, H. Z. Zhao, and J. E. Thomas, "Bloch vector projection noise," in Conference Proceedings, Third International Workshop on Squeezed States and Uncertainty Relations, (Baltimore, August 10-13 1993).

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New Applications of Noise Measurement Methods

7) A. Wax and J. E. Thomas, "Heterodyne measurement of Wigner phase space distributions in Turbid Media," OSA Trends in Optics and Photonics on Advances in Optical Imaging and Photon Migration, R. R. Alfano and James G. Fujimoto, eds. (Optical Society of America, Washington, DC 1996), Vol. 2, pp. 238-242.

8) A. Wax and J. E. Thomas, "Optical heterodyne imaging and Wigner phase space distributions," Opt. Lett. **21**, 1427 (1996).

Additional Research on Precision Position Measurement of Moving Atoms, (Supported in Part)

9) J. E. Thomas, J. R. Gardner, G. R. Welch, M. L. Marable, T. A. Savard, and L. J. Wang, "Uncertainty-principle-limited position measurement of moving atoms," in Quantum Optics VI, D. F. Walls, and J. D. Harvey, eds., Vol. 77, Springer Proceedings in Physics (Springer-Verlag, New York, 1994), pp. 27-35.

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4 Students Participating in this Research

1) Carl Schnurr (Ph.D., Physics, Duke University, May, 1994).
2) Allan Bacon (Ph. D., Physics, Duke University, May, 1995).
3) Tom Savard
4) Adam Wax
5) Ken O'Hara
6) Chris Baird (M. S., Physics, Duke University, May, 1996).
7) Mike Gehm (Summer)
8) Steve Granade (Summer)

5 Patents and Inventions

None.