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Novel Approaches to Sensitivity Enhancement of Ring Laser Gyros

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For Acceleration Project on Squeezed States for a Noise Reduction in Interferometers

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Summary of Work Accomplished

The considerable body of work accomplished under the auspices of this grant has been reported in 40 published papers. A list of these papers are given below. A main theme of ~~most of~~ these papers are the role of quantum effects and determining how the sensitivity of optical senor, such as the ring-laser gyro, can be improved. We summarize this work below, with references to the attached publication list.

The correlated-spontaneous-emission laser (CEL) is a concept first developed by us in 1985 which permits reduction of quantum noise associated with the relative phase angle between two correlated laser transitions. The mechanism of quantum noise quenching in the original CEL device (quantum beat laser) has been explained using a geometrical approach (~~Paper~~ 15), and a more rigorous analysis where amplitude noise is also included. Extensive studies on the CEL, including the effects of nonlinear saturation and atomic motion, was performed ~~in paper~~ 7 - 9. The CEL concept has been found applicable to various types of devices, besides the quantum beat laser, for the purpose of quantum noise reduction. Using the CEL concept, we have developed the following four devices, which have the ability of quantum noise reduction, even squeezing.

1. Memory Effect Laser (paper 11)

   The phase noise in a laser with short lifetime active medium is the famous Schawlow-Townes result. In memory effect lasers we use long lifetime atoms as the active medium (as compared with the measurement time). The phase noise can be dramatically reduced due to the atomic memory effect. This noise reduction is valid even though the saturation is taken into account.

2. Holographic Laser (paper 1)

   In holographic lasers the active medium in a ring cavity is modulated like a hologram. The two counterpropagating beams interfere constructively with each other, which leads to noise quenching. This noise quenching is maintained in third order. This holographic laser is very useful in the sensitivity enhancement of Ring Laser Gyros.

3. Hanle Laser (paper 3)

The Hanle laser is a similar device to the quantum beat CEL with the use of two different polarized beams.

4. Two-Photon CEL (paper 4)

The two photon CEL device has the ability to produce squeezed state radiation fields and is a potential bright source of squeezed light. Because of this, we have done a lot of work on the two-photon CEL. We studied the phase noise squeezing in linear and nonlinear theories (papers 4, 6, 23, 25). A number of analytical approaches have been proved useful in understanding the two-photon CEL (papers 4, 26, 32, 35, 40).

Papers 20 and 21 are conference proceedings providing an overview of the various devices, which have the ability of quantum noise reduction, quenching and squeezing. The influence of pumping statistics and the squeezing relation between the inside cavity and outside cavity have been studied in papers 28, 38, and 39. Comparison has been made to the results of experiment (paper 14).

Besides the quantum noise reduction, quenching and squeezing, we, using the CEL concept, have developed a new kind of laser device which can be operated with nonpopulation inversion (paper 31).

Quantum noise reduction, through the generation and use of squeezed states, is a technique which has proven to be experimentally effective. Papers 3, 24, 33, 38, and 39 are concerned with the physical understanding of squeezed states and the applications of such states to sensitivity enhancement.

In paper 38, a physically intuitive picture of the relation of quantum fluctuations inside and outside a transmitting cavity was developed. The principal tenet of this work was the analysis of quasimodes of a leaky cavity in terms of the true modes of a larger (infinitely large in the limit) cavity containing the leaky one. Based on this description, one could easily understand why quantum noise reduction, and specifically the degree of squeezing, is different inside and outside. This has much relevance to the study of sensitivity enhancement of laser gyros, since what one might predict for squeezing inside may be quite different from that in the output light which is what one typically will use. In fact, there may be dramatic differences inside and outside: in particular, if the intracavity field is perfectly squeezed, than the output field shows no squeezing at all.

In paper 39, applications of this physical picture to the intracavity - extracavity quadrature variance relations for an ordinary laser, a laser operating in the phase-locked regime, and to a 2-photon correlated emission laser were studied. In the last system, under two different conditions, we found, respectively, 50% intracavity and 100% extracavity phase squeezing, and 100% intracavity and no extracavity phase squeezing.

Paper 13 represents the initial efforts to address phase diffusion and quantum noise responsible for the intrinsic linewidth of a laser when the laser cavity has low Q. This has relevance to the sensitivity questions already addressed in this report, but also to the case of semiconductor lasers with simply cleaved, unpolished facets. As one expects, the phase diffusion and quantum noise impressed upon the laser light output tend to increase as the cavity transmission increases. This initial effort has now been put on much more solid ground via a single-quasimode, Langevin picture as well as (for extremely low-Q cavities) via a nonmodal difference-equation analysis (papers to be published). Also, extensions to the case of injection of squeezed vacuum are now more or less complete, confirming the results of paper 3 which showed that by squeezing the injected vacuum perfectly, one could reduce the laser linewidth by 50%.

Finally, we note that the role of an observer in several experiments has been investigated using the micromaser as a which-path detector. In this work we have accomplished Einstein's goal and achieving which-path information without scrambling phases of the carrier waves. However, quantum complementarity is still preserved via quantum correlations so that Bohr would not be unhappy with these results.

Index of Grant-Supported Publications:

1. J. Krause and M. O. Scully, "Theory of the Holographic Laser: Correlated Emission in a Ring Cavity," Phys. Rev. A 36, 1771 (1987).

2. J. Krause, M. O. Scully, and H. Walther, "State Reduction and |n> - State Preparation in a High-Q Micromaser," Phys. Rev. A 36, 4547 (1987).

3. J. Gea-Banacloche, "Squeezing of Spontaneous Emission in a Laser," Phys. Rev. Lett. 59, 543 (1987).

4. M. O. Scully, K. Wodkiewicz, M. S. Zubairy, J. Bergou, N. Lu, and J. Meyer-Ter-Vehn, "Two-Photon Correlated-Spontaneous-Emission Laser: Quantum Noise Quenching and Squeezing," Phys. Rev. Letters 60, 1832 (1988).

5. K. Wodkiewicz, "Stochastic Description of Vacuum Fluctuations," Phys. Rev. A 38, 2932 (1988).

6. M. O. Scully and M. S. Zubairy, "Noise-Free Amplification Via the Two-Photon Correlated Spontaneous Emission Laser," Opt. Commun., 66, 303 (1988).

7. K. Zaheer and M. S. Zubairy, "Nonlinear Theory of a Correlated Emission Laser," Phys. Rev. A 38, 5227 (1988).

8. J. Bergou, M. Orszag, and M. O. Scully, "Correlated-Emission Laser: Phase Noise Quenching Via Coherent Pumping and the Effect of Atomic Motion," Phys. Rev. A 38, 768 (1988).

9. J. Bergou, M. Orszag, and M. O. Scully, "Correlated-Emission Laser: Nonlinear Theory of the Quantum-Beat Laser," Phys. Rev. A 38, 754 (1988).

10. J. Bergou and M. Orszag, "Correlated-Emission Laser: Theory of the Quantum-Beat Micromaser," Phys. Rev. A 38, 763 (1988).

11. M. O. Scully, G. Suessmann, and C. Benkert, "Quantum Noise Reduction Via Maser Memory Effect: Theory and Applications," Phys. Rev. Lett. 60, 1014 (1988).

12. M. O. Scully, M. S. Zubairy, and K. Wodkiewicz, "Atomic Memory Effects in the Quantum Theory of the Laser," Opt. Commun. 65, 440 (1988).

13. S. Prasad and B. S. Abbott, "Mirror Transmission and Laser Phase Diffusion in the Quantum Regime," Phys. Rev. A 38, 3551 (1988).

14. J. Bergou and M. Orszag, "A Dynamically Correlated Spontaneous Emission Laser: Theory and Comparison to Experiment," J. Opt. Soc. of America B 5, 249 (1988).

15. W. Schleich and M. O. Scully, "Quantum-Noise Quenching in the Correlated Spontaneous Emission Laser as a Multiplicative Noise Process. I. A Geometrical Argument," Phys. Rev. A 37, 1261 (1988).

16 W. Schleich, M. O. Scully, and H.-G. von Garssen, "Quantum-Noise Quenching in the Correlated Spontaneous Emission Laser as a Multiplicative Noise Process. II. Rigorous Analysis Including Amplitude Noise," Phys. Rev. A 37 3010 (1988).

17. S.-Y. Zhu and M. O. Scully, "Photon Statistics and Quantum Fluctuation in the Two-Photon Jaynes-Cummings Model," Phys. Lett. A 133, 95 (1988).

18. B.-G. Englert, J. Schwinger, and M. O. Scully, "Is Spin Coherence Like Humpty-Dumpty? I. Simplified Treatment," Found. of Phys. 18, 1045 (1988).

19. J. Schwinger, M. O. Scully and B.-G. Englert, "Is Spin Coherence Like Humpty-Dumpty? II. General Theory," Z. Phys. D. 10, 135 (1988).

20. C. Benkert, W. Schleich and M. O. Scully, "A Physical Picture of the Two-Photon Correlated Spontaneous Emission Laser," Proc. 11th Int. Conf. on Atomic Physics, 1988, to be published by World Scientific Publishing Co.

21. M. Orszag, J. Bergou, W. Schleich, and M. O. Scully, "The Correlated Spontaneous Emission Laser: Theory and Recent Developments," invited paper published in Squeezed and Non-Classical Light, Proceedings of the NATO Advanced Research Workshop, Cortina, Italy, Jan. 25-29, 1988, ed. by P. Tombesi and R. Pike, Plenum, New York, 1988, p. 287.

22. J. A. Bergou and M. O. Scully, "Quantum Theory of the Hanle Laser and its Use as a Metric Gravity Probe," in Hanle Effect and Level Crossing, ed. by F. Strumia and G. Moruzzi, (Plenum, London, 1988).

23. Ning Lu, Fang-Xiao Zhao, and J. Bergou, "Nonlinear Theory of a Two-Photon Correlated-Spontaneous Emission Laser: A Coherently Pumped Two-Level-Two Photon Laser," Phys. Rev. A 39, 5189 (1989).

24. J. Bergou, M. Orszag, and M. O. Scully, "Squeezing and Quantum-Noise Quenching in Phase-Sensitive Optical System," Phys. Rev. A 39, 5136 (1989).

25. N. Lu, and J. Bergou, "Quantum Theory of a Laser With Injected Atomic Coherence: Quantum Noise Quenching Via Nonlinear Processes," Phys. Rev. A 40, 237 (1989).

26. N. Lu, S-Y. Zhu, G. S. Argawal, "Comparative Study of Various Quasiprobability Distribution in Different Models of Correlated-Emission Lasers," Phys. Rev. A 40, 258 (1989).

27. N. Lu, et al., "Theory of a Coherently Pumped Maser in Various Cavity." (June 89) Optics Commun. 72, 319 (1989).

28. J. Bergou, L. Davidovich, M. Orszag, C. Benkert, M. Hillery and M. O. Scully, "Influence of the Pumping Statistics in Laser and Masers," Opt. Commun. 72, 82 (1989).

29. M. O. Scully, B.-G. Englert, and J. Schwinger, " Spin Coherence and Humpty Dumpty: III The Effects of Observation," Phys. Rev. A 40, 1775 (1989).

30. N. Lu, "Effects of Dissipation on Photon Statistics and the Lifetime of a Pure Number State," Phys. Rev. A 40, 1707 (1989).

31. M. O. Scully. S-Y. Zhu, and A. Gavrielides, "Degenerate Quantum-Beat Laser: Lasing Without Inversion and Inversion Without Lasing," Phys. Rev. Lett. 62, 2813 (1989).

32. J. Bergou, N. Lu, and M. O. Scully, "The Two-Photon Correlated-Spontaneous- Emission Laser in a Squeezed Vacuum," Opt. Commun. 73, 57 (1989).

33. Ning Lu and Janos A. Bergou, "Effects of a Squeezed Vacuum on a Laser Exhibiting Phase Locking: An Application to a Laser with Injected Atomic Coherence," Phys. Rev. A 40, 250, (1989).

34. Joachim Krause, Marlan O. Scully, Thomas Walther and Herbert Walther, "Preparation of a Pure Number State and Measurement of the Photon Statistics in a High-Q Micromaser," Phys. Rev. A 39, 1915 (1989).

35. Ning Lu and Shi-Yao Zhu, "Quantum Theory of Two-Photon Correlated-Spontaneous-Emission Lasers: Exact Atom-Field Interaction Hamiltonian Approach," Phys. Rev. A 40, 5735 (1989).

36. J. Bergou, L. Davidovich, and M. Orszag, "Role of Pumping Statistics in Maser and Laser Dynamics: Density-Matrix Approach," Phys. Rev. A 40, 5073 (1989).

37. Shi-Yao Zhu and Ning Lu, "On the Expectation Values Found from the Glauber- Sudarshan and Positive P-Representations," Phys. Lett. A 137, 191 (1989).

38. Julio Gea-Banacloche, Ning Lu, Leno M. Pedrotti, Sudhakar Prasad, Marlan O. Scully, and Krzystof Wodkiewicz, "Treatment of Spectrum of Squeezing Based on the Modes of the Universe. I. Theory and a Physical Picture," Phys. Rev. A 41, 369 (1990).

39. Julio Gea-Banacloche, Ning Lu, Leno M. Pedrotti, Sudhakar Prasad, Marlan O. Scully, and Krzystof Wodkiewicz, "Treatment of Spectrum of Squeezing Based on the Modes of the Universe. II. Applications," Phys. Rev. A 41, 381 (1990).

40. Shi-Yao Zhu and Ning Lu, "Positive P-Representation Approach for a Two-Photon Correlated-Spontaneous-Emission Laser," Phys. Lett. A 138, 55 (1989).

Invited Presentations at Topical or Scientific/Technical Society Conferences:

41. M. O. Scully, "Two-Photon Correlated Spontaneous Emission Laser," The International Paris Conference on Atomic Physics, 1988.

42. M. O. Scully, "Overcoming Quantum Noise," Winter colloquium on Quantum Electronics, Snowbird, Utah, Jan., 1988.

43. M. O. Scully, "Correlated Spontaneous Emission Lasers," Wigner Symposium, 1988.

44. S. Prasad, "Laser Phase Diffusion: Its Dependence on Mirror Transmission and Short-Time Behavior," XIth International Conference on Atomic Physics, Paris, France, July, 1988.