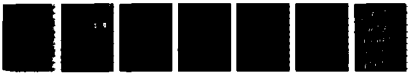
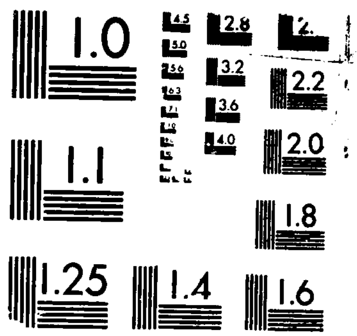
AD-A194 410 FINAL REPORT FOR CALTECH (CALIFORNIA INSTITUTE OF TECHNOLOGY) CONTRACT NO..(U) CALIFORNIA INST OF TECH PASADENA 30 NOV 87 N00014-85-K-0005 1/1

UNCLASSIFIED F/G 20/10 NL





MICROCOPY RESOLUTION TEST CHART
URFAU OF STANDARDS-1963-A

(4)

CALTECH

THEORETICAL ASTROPHYSICS 130-33
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA 91125
USA

TELEPHONE: (818)356-4597

1988 February 26

Dr. Herschel Pilloff
Office of Naval Research
Physics Division (Code 1112LO)
800 North Quincy Street
Arlington, Virginia 22217-5000

Dear Hersch,

This is the final technical report of work accomplished under ONR Contract No. N00014-85-K-0005 at Caltech during the period 1984 October 1 to 1987 November 30. The body of the letter summarizes work accomplished under this contract; addenda to the letter list publications and persons associated with the contract. In the summary names of persons associated with the contract are in italics, and publications are referred to by number.

- *Caves* and *Schumaker* developed a formalism for describing two-photon processes—the kind of processes that produce squeezed-state light [1, 2, 8, 14]. The aim of this formalism was to provide a natural and convenient way of describing and analyzing broadband squeezed-state light. The formalism is based on a set of variables called the quadrature-phase amplitudes [1], which are the temporal Fourier components of the quadrature components of the electromagnetic field, defined relative to some carrier frequency. The second-order noise moments of the quadrature-phase amplitudes yield a spectral-density matrix which contains information about the fluctuations of squeezed-state light.

The *Caves-Schumaker* formalism was the foundation for much of the work on squeezed-state light at Caltech: *Schumaker's* work on quasiprobability distributions (QPDs) and ultrasqueezing (described below), *Caves* and *Crouch's* spatial Langevin formalism for a degenerate parametric amplifier (supported by a Caltech PAT grant), *Braunstein* and *Caves's* attempt to use the *Schumaker* QPDs in analyzing parametric amplifiers and oscillators (described below), and *Caves's* work on laser stabilization (described below). The formalism has also been used by Gea-Banacloche and Leuchs in work on squeezed-state interferometry and by Gea-Banacloche in an analysis of what happens when squeezed-state light is fed into a laser oscillator.

- *Schumaker* defined a new set of quasiprobability distribution (QPDs) based on natural orderings of the quadrature-phase amplitudes. These QPDs can be used to convert a master equation into an equivalent Fokker-Planck equation, which can under some circumstances be converted into a set of c-number stochastic differential equations. It is hoped that these QPDs can be used to analyze generators of squeezed-state light. Schumaker has not yet written an extensive account of her new QPDs.

- *Schumaker* carried out an extensive investigation of multimode quantum states that have Gaussian wave functions [3]. She explored in detail the properties of such states, which are the states produced by ideal two-photon processes and which encompass all the states that display ideal squeezing. This work formed a substantial portion of her Ph.D. thesis, and it was the basis for subsequent work on ultrasqueezing (described below).

- *Schumaker* derived a generalised quantum-mechanical uncertainty principle which constrains the variances of four complex, noncommuting quantities. These generalised uncertainty principles are directly relevant to the noise properties of squeesed-state light. *Schumaker* has not yet written up this work for publication.

- *Caves*, joined briefly by *Weber*, worked intermittently on a broadband quantum theory of photodetection [12], which is necessary for a description of fast photodetectors and, in particular, for a proper analysis of the detection of broadband squeesed light. To construct such a theory, one must correct a fundamental defect in the standard Glauber theory—that it does not include spatial attenuation within the detector. *Caves* has identified the assumption in the Glauber theory which must be modified in order to handle spatial attenuation and has made some progress in developing a modified theory. This work, however, has been on hold since a burst of activity early in 1986.

- *Schumaker*, together with collaborators at IBM Almaden Research Center in San Jose, developed the theory of ultrasqueesed light [4, 8, 13]—the sort of light produced by two-photon processes when multiple pump frequencies are used so that more than two frequencies are correlated by the two-photon nonlinearity. In the squeesing experiment at IBM ultrasqueesed light has been easier to produce than ordinary squeesed light.

- *Braunstein*, in collaboration with Robert McLachlan, a graduate student in Applied Mathematics at Caltech, explored numerically a kind of generalised squeesing [5, 16]. Ordinary squeesing is produced by interactions that are quadratic in creation and annihilation operators (two-photon processes). *Braunstein* and McLachlan analysed interactions that are cubic or higher order in creation and annihilation operators (three-photon and higher processes). There had been suggestions that such higher-order interactions lead to an ill-defined unitary evolution operator, but the numerical work of *Braunstein* and McLachlan showed this not to be the case. Their work has potential application to the production of ordinary squeesed light.

- *Braunstein* and *Caves*, together with Gerard Milburn of The Australian National University, sought to give a physical interpretation for the positive P-representation. The positive P-representation, a commonly used tool for analysing generation of squeesed-state light and for handling other problems in nonlinear optics, requires doubling the number of phase-space dimensions; its major drawback is that it has not had any physical interpretation. *Braunstein*, Milburn, and *Caves* have succeeded in interpreting a particular form of the positive P-representation—which they call the canonical form—in terms of position and momentum measurements made by two sets of Arthurs-Kelly meters. This work is potentially quite important, but it is not yet clear whether it can be used to understand the pathologies that arise when stochastic differential equations derived using the positive P-representation are simulated on a computer.

- *Braunstein* and *Caves* attempted to apply the *Schumaker* QPDs to an analysis of a parametric amplifier or oscillator with a quantum pump. Their goal was to start with a master equation and to derive a Fokker-Planck equation which has a sensible physical interpretation and which can be converted into an equivalent set of stochastic differential equations. This goal requires that the Fokker-Planck equation be written in terms of ordinary phase-space variables (compare the oft-used positive P-representation, mentioned above), that it have derivatives no higher than second order, and that it have a positive-definite diffusion matrix. Although this goal has not been achieved, not all the freedom of the *Schumaker* QPDs has yet been explored.

- *Caves* began investigating the application of squeesed-state light to laser stabilization [6, 9, 17]. He considered the Machida-Yamamoto configuration, in which negative feedback from a conventional photodetector is used to stabilise a laser's intensity and out-of-loop light is extracted at a beamsplitter. The crucial change was to replace the vacuum field incident on the beamsplitter's second input port with squeesed light. Using a formalism developed by Shapiro *et al.*, *Caves* showed that in such a system of feedback with squeesing, the extracted light can have sub-shot-noise statistics [6]. Furthermore, the intensity signal-to-noise ratio of a shot-noise-limited laser can be improved by this technique, even though the extracted light does not carry all the power of the unstabilised laser. In addition to investigating intensity stabilisation, *Caves* began work on applying squeesing to laser frequency stabilisation [9].

• *Braunstein* and *Crouch* analysed both numerically and analytically the parametric amplifier with a quantum-mechanical pump. Their objective was partly to resolve a discrepancy between previous analytical results. Hillery and Zubairy and, later, *Caves* and *Crouch* claimed to find the dominant effect of pump quantum fluctuations in a paramp, but Scharf and Walls, using a seemingly more sophisticated method of analysis, found a much more serious effect. *Braunstein* and *Crouch* have shown that the Scharf-Walls result is incorrect, and they have also investigated in detail the effect of pump quantum fluctuations on both degenerate and nondegenerate paramps.

Sincerely,

Carlton M. Caves

Carlton M. Caves

CMC/TEX

LIST OF PUBLICATIONS

Contract No. N00014-85-K-0005 (1984 October 1 to 1987 November 30)

1. Technical articles in refereed journals

[1] C. M. Caves and B. L. Schumaker, "New formalism for two-photon quantum optics. I. Quadrature phases and squeezed states," *Phys. Rev. A* **31**, 3068 (1985).

[2] B. L. Schumaker and C. M. Caves, "New formalism for two-photon quantum optics. II. Mathematical foundation and compact notation," *Phys. Rev. A* **31**, 3093 (1985).

[3] B. L. Schumaker, "Quantum-mechanical pure states with Gaussian wave functions," *Phys. Rep.* **135**, 317 (1986).

[4] B. L. Schumaker, S. H. Perlmutter, R. M. Shelby, and M. D. Levenson, "Four-mode squeezing," *Phys. Rev. Lett.* **58**, 357 (1987).

[5] S. L. Braunstein and R. I. McLachlan, "Generalised squeezing," *Phys. Rev. A* **35**, 1659 (1987).

[6] C. M. Caves, "Squeezing more out a laser," *Opt. Lett.* **12**, 971 (1987).

2. Other technical articles

[7] C. M. Caves, "Amplitude and phase in quantum optics," in *Coherence, Cooperation and Fluctuations*, edited by F. Haake, L. M. Narducci, and D. F. Walls (Cambridge University, Cambridge, England, 1986), p. 192.

[8] C. M. Caves and B. L. Schumaker, "Broadband squeezing," in *Quantum Optics IV*, edited by J. D. Harvey and D. F. Walls (Springer, Berlin, 1986), p. 20.

[9] C. M. Caves, "Application of squeezed-state light to laser stabilisation," in *Laser Spectroscopy VIII*, edited by S. Svanberg and W. Persson (Springer, Berlin, 1987), p. 146.

[10] C. M. Caves, "Optical squeezing," in *1989 Yearbook of Science and Technology*, edited by S. P. Parker (McGraw-Hill, New York, to be published).

[11] D. D. Crouch, "Squeezed states of the electromagnetic field," section contributed to third edition of A. Yariv, *Quantum Electronics* (Wiley, New York, to be published).

3. Abstracts of papers presented at meetings

[12] C. M. Caves, "Photocount statistics of broadband squeezed states," *J. Opt. Soc. Am. A* **2**(13), P92 (1985).

[13] B. L. Schumaker, "What is a broadband squeezed state?" *J. Opt. Soc. Am. A* **2**(13), P92 (1985).

[14] C. M. Caves and B. L. Schumaker, "Broadband squeezing," in *Proceedings of the MIT Endicott House Workshop on Squeezed States of Light*, 1985 October 21–25 (1985).

[15] C. M. Caves, "Application of squeezed-state light to high-precision interferometry," *J. Opt. Soc. Am. A* **3**(13), P37 (1986).

[16] S. L. Braunstein and R. McLachlan, "Generalised squeezing," *J. Opt. Soc. Am. A* **3**(13), P46 (1986).

[17] C. M. Caves, "Squeezing more out of a laser," *J. Opt. Soc. Am. A*, to be published.

LIST OF PERSONNEL

Contract No. N00014-85-K-0005 (1984 October 1 to 1987 November 30)

- *Carlton M. Caves.* Senior Research Fellow in Theoretical Physics and principal investigator. Partial salary support throughout contract.
- *Bonny L. Schumaker.* Graduate student (84–10 till 85–5)—full support as a Graduate Research Assistant. Postdoctoral Research Fellow (85–6 till 86–5)—partial salary support. Now at the Jet Propulsion Laboratory (JPL).
- *Samuel L. Braunstein.* Graduate student (85–10 till present)—full support as a Graduate Research Assistant during summer 1987. Ph.D. expected before end of summer 1988.
- *David D. Crouch.* Graduate student (85–10 till present)—no direct support from this contract. Ph.D. expected before end of summer 1988.
- *Walter Weber.* Graduate student (85–10 till 86–9)—no direct support from this contract. Left Caltech and later returned to another research group.

END
DATE
FILMED
8-88
DTIC