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 summarises 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 analysing 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 analysing 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 analyse 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 squeezed-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 squeezed 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 ultrasqueezed 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 squeezing experiment at IBM ultrasqueezed light has been easier to produce than ordinary squeezed light.

Braunstein, in collaboration with Robert McLachlan, a graduate student in Applied Mathematics at Caltech, explored numerically a kind of generalised squeezing [5, 16]. Ordinary squeezing 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 squeezed 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 squeezed-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 squeezed-state light to laser stabilisation [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 squeezed light. Using a formalism developed by Shapiro et al., Caves showed that in such a system of feedback with squeezing, 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 unstabilized laser. In addition to investigating intensity stabilisation, Caves began work on applying squeezing 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

CMC/TpX
LIST OF PUBLICATIONS

1. Technical articles in refereed journals


2. Other technical articles


3. Abstracts of papers presented at meetings


LIST OF PERSONNEL

- 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).
- 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.
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