Interferometric Measurement of Quantum Noise in a Raman Amplifier

R. C. Swanson, P. R. Battle, and J. L. Carlsten
Physics Department, Montana State University, Bozeman, Montana 59717
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How large must the input signal to an amplifier be to dominate the quantum noise introduced during amplification? We attempt to answer this question for a Raman amplifier with an experiment that utilizes a modified Mach-Zender interferometer with an amplifier placed in each leg. The quantum noise added by the amplifiers manifests itself by degrading the visibility of the output fringes from the interferometer. Only an average of a few photons per mode were necessary to achieve good visibility.

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The role of amplifiers in physics has long been a central concern. This is especially true when amplifiers are used to transform "quantum" signals to "classical" signals such as in the famous example of Schrödinger's cat paradox. Glauber [1] has discussed the role of amplifiers in this gedanken experiment and has shown that the central stumbling block to superpositions of alive and dead cats lies in the amplifier. It has been shown that even with an ideal linear amplifier, quantum noise is necessarily added [2–4] and corresponds to at least one photon per mode at the input to a noiseless amplifier. (The term "linear" means the output signal is linearly related to the input signal.) The origin of this quantum noise can be traced to the fundamental commutation relations of the amplifier. Thus the noise does not arise from an "imperfection" in the amplifier; it is fundamentally required by the Heisenberg uncertainty principle.

While early experiments [5,6] showed that the noise power emitted from a laser gain tube approaches what one would expect from the quantum limit, recent interest has centered on determining how large an input signal is needed to dominate this quantum noise added by the amplifier. For example, Duncan *et al.* [7] have observed that an average of 300 photons per spatial mode were needed to control the output spatial mode in a Raman amplifier. In another experiment using a quantum amplifier, Kulagin, Pasmanik, and Shilov [8] have found that as few as five photons per spatial mode are needed to operate a highly sensitive phase-conjugating projection system. Recent experiments [9] have also found that the noise added to the input signal by fiber amplifiers is close to the quantum limit. In this Letter we describe an experiment using an interferometer with an amplifier in each leg to show that even with average injection levels of one photon per mode, the fringe visibility due to the amplification of the input signal is observable.

Our experiment is diagramed in Fig. 1. We will discuss the essentials of this experiment now and save the various experimental details for later in this Letter. Basically, the experiment consisted of a Raman generator that provided the input signal to an interferometer. Separate, identical Raman amplifiers were inserted into each leg of the interferometer [10]. These amplifiers transformed the small input signals into large, macroscopic output signals, but also added noise due to amplified spontaneous emission. To quantify the effect of this added noise, we calculated the visibility of the output fringe pattern from the interferometer:

$$V=\frac{\langle\hat{I}\rangle_{\max}-\langle\hat{I}\rangle_{\min}}{\langle\hat{I}\rangle_{\max}+\langle\hat{I}\rangle_{\min}}, \tag{1}$$

where V is the visibility, $\langle\hat{I}\rangle_{\max}$ is the maximum intensity of the ensemble fringe pattern, and $\langle\hat{I}\rangle_{\min}$ is the minimum intensity of the ensemble fringe pattern.

The output field from the amplifier consists of a superposition between the amplified field arising from spontaneous emission in the amplifier (the noise) and the amplified field due to stimulated emission of the input signal [11]. These two fields lead to very different visibilities. It has been shown that the amplified fields arising from spontaneous emission in two separate Raman amplifiers are uncorrelated in phase [12]. Consequently, the position of the peaks and troughs in the output fringe pattern vary from shot to shot and the ensemble average of the fringe patterns has a visibility of 0. On the other hand, the amplified input signals are correlated since the

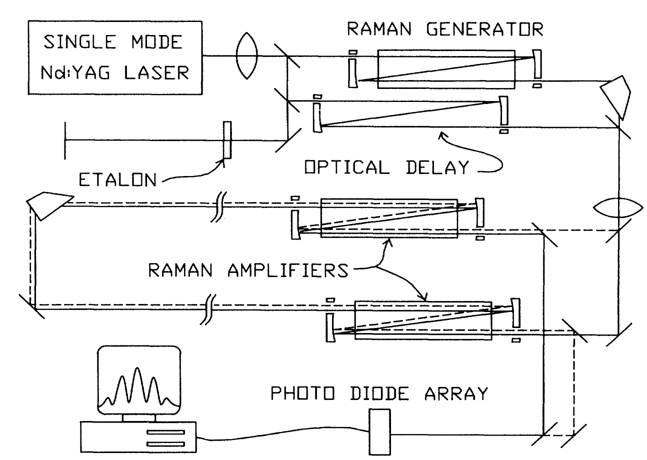

FIG. 1. Experimental apparatus used to study quantum noise. One beam path in the interferometer is indicated by a dashed line, and the other by a solid line. The output fringe pattern is imaged onto a linear photodiode array for data collection.

inputs are correlated. Thus the two outputs produce stationary fringes from shot to shot, and therefore the ensemble-average fringe pattern has good visibility.

One then sees that ensembles with large visibilities are dominated by the amplified input signal, and those with small visibilities are dominated by the amplified spontaneous emission (noise). As one would expect, when the input signal to the interferometer is very weak the visibility is low, but as the input signal gets larger, the visibility approaches 1. This leads one to ask the question: How large must the input signal be to dominate the noise?

To answer the above question theoretically we used the fully quantum theory of Raman scattering [13,14] to calculate the visibility. These rather involved calculations lead to a result that is unfortunately too long and complicated to be presented here but will be given in a future article. If, however, one replaces the Raman amplifiers in the experimental setup shown in Fig. 1 with ideal, single-mode amplifiers [2], a concise expression for the visibility may be found which predicts a visibility very similar to that for the fully quantum Raman theory [15]:

$$V=\frac{\langle \hat{b}_G^\dagger \hat{b}_G\rangle}{\langle \hat{b}_G^\dagger \hat{b}_G\rangle+(1-|M|^{-2})/2T_{bs}R_{bs}T_{po}}\,. \tag{2}$$

In Eq. (2) the term $\langle \hat{b}_G^\dagger \hat{b}_G\rangle$ is the average number of photons input to the interferometer, $|M|^{-2}$ is the inverse of the gain in the amplifiers, T_{bs} is the transmittance of the identical input and exit beam splitters of the interferometer, R_{bs} is the reflectance of the input and exit beam splitters, and T_{po} is the transmittance of the identical pickoff optics (the optics where the solid and dashed lines diverge when inside the interferometer in Fig. 1).

The second term in the denominator is due to the noise added by the amplifiers. In Eq. (2) one can see that when the gain $|M|^2$ is 1 (no amplification), then the noise plays no role, as expected in a passive interferometer. Also note that when the amplifier gain is large, the visibility is insensitive to small variations in the gain. This is quite reasonable since once the signal has been amplified by several orders of magnitude, one would not expect the spontaneous emission added during further amplification to be significant.

If the input and exit beam splitters are chosen to have 50/50 transmission/reflection ratios ($T_{bs}=R_{bs}=0.5$) and if T_{po} is approximately 1, the effect of the noise is minimized and hence the visibility is maximized. With the above choices of beam splitters and the amplifiers operating at high gain, the noise term [second term in the denominator in Eq. (2)] is equal to the input signal when an average of two photons are input to the interferometer, or, when one photon on average is input to each amplifier. With this input, the visibility is $\frac{1}{2}$. Doubling the input signal yields a visibility of $\frac{2}{3}$. Thus one can see that the visibility is a very sensitive measure of the relationship between the input signal and the amplifier-added noise for low photon numbers.

To test the predictions of this theory we performed the experiment outlined schematically in Fig. 1. A pulsed, near-single-mode, frequency-doubled Nd-doped yttrium-aluminum-garnet laser with a full width at half maximum temporal profile of 14.6 ns was used to pump a Raman generator that consisted of a cell of H_2 at 10 atm placed in a multipass cell. The pump energy input to the Raman generator was adjusted to a desired value by varying attenuators (not shown in Fig. 1) in front of the generator. To insure that no mode hops of the pump laser occurred during data runs, the pump frequency was monitored with an etalon. A power meter (not shown in Fig. 1) recorded the input energy of every pump shot. The resulting down-shifted Stokes light from the generator became the input signal to the interferometer. This input was combined with more pump for the amplification in the Raman amplifiers which were also placed in multipass cells. The peak pump intensity in the amplifiers was ~ 5 MW/cm^2, which led to amplifications of around 10 orders of magnitude in the thirteen passes of the multipass cells. However, the amplification was never so large as to lead to pump depletion.

In Fig. 1, one beam path has been drawn as a dashed line to distinguish it from the other beam path in the interferometer. The input beam splitter to the interferometer split the pump energy equally to within 1% to insure equal pumping of the amplifiers. At the Stokes frequency, however, the reflectance was $R_{bs}=0.22$ and the transmittance was $T_{bs}=0.78$. The interferometer was nearly cyclic; thus in most of the interferometer both beams experienced the same optics. This greatly increased the stability of the interferometer as compared to a true Mach-Zender interferometer. The few optics experienced by only one of the beam paths allowed easy adjustment of the beams to obtain the desired fringe spacing. The transmittance of the pickoff mirrors at the Stokes frequency was $T_{po}=0.5$.

The two beam paths indicated experienced separate Raman amplifiers as they traversed the interferometer. After amplification, the residual pump was removed from the beam with a modified Pellenbroca prism. Additionally, an optical delay between the two amplifiers made sure that the pulses never overlapped inside an amplifier. Consequently, the amplifications of the two pulses were independent of each other. The pump fields that were removed from the interferometer were monitored with fast photodiodes (not shown in Fig. 1) to insure that no pump depletion occurred that would lead to nonlinear amplification.

The amplified beams were then combined at the exit beam splitter (identical to the input beam splitter) and the resulting fringe pattern was imaged onto a linear photodiode array [16]. The photodiode array output was digitized and interfaced to a computer for data collection and analysis. Each shot was interpreted as a realization

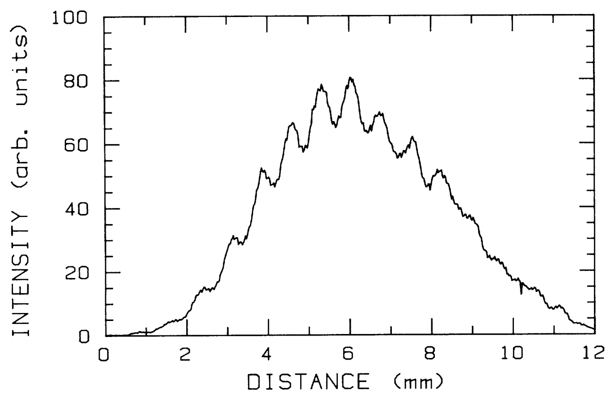

FIG. 2. Ensemble average of 244 fringe patterns. The input signals had an average of 0.28 photon per mode input into each amplifier in the interferometer. The measured visibility was 0.1.

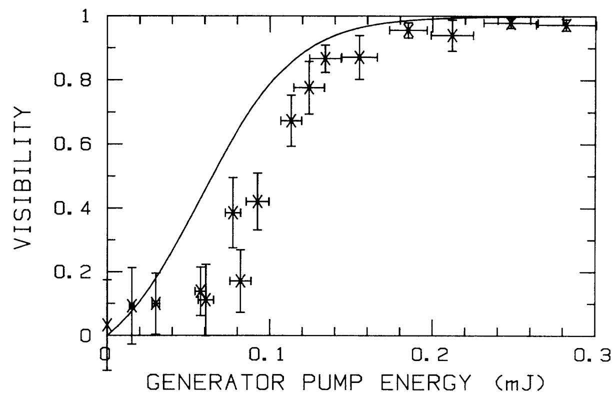

FIG. 4. Visibility as a function of pump energy input to the Raman generator. The individual data points indicate experimental data and the curve gives the results from theory.

of the ensemble, so the ensemble average of the shots was compared to the quantum-mechanical prediction.

Figures 2 and 3 show two typical ensemble averages with the amplifiers turned on. In Fig. 2, we present the ensemble average of 244 shots that had input signals with an average of 0.28 photon per mode per amplifier. We measured a visibility of 0.1 for this ensemble. In Fig. 3 the input signal had an average of 1.9 input photons per mode per amplifier with a resulting visibility of 0.39, showing that the larger the input signal, the better the visibility.

In Fig. 4 we present the experimentally measured visibility (crosses) as a function of the input pump energy to the Raman generator. This graph shows that as the pump energy to the Raman generator increases (i.e., the input signal to the amplifiers increases), the visibility approaches 1, indicating the amplified signal dominates the quantum noise. Also shown in Fig. 4 as a solid curve are the theoretical results based on the full quantum-mechanical theory of Raman scattering [13,14]. Experimentally, the photodiodes that recorded the fringe pattern integrated the intensity over the duration of the pulse. Therefore we integrated the theoretical intensity expectation values over the pulse to compare with experiment [17]. The error bars in the data are based on estimates of measurement errors but do not include possible slight misalignment of various beams which can lead to a downward shift of the data relative to the theoretical curve.

To fully appreciate the implications of these measurements we transformed the horizontal axis of Fig. 4 into units of average number of photons per mode input into

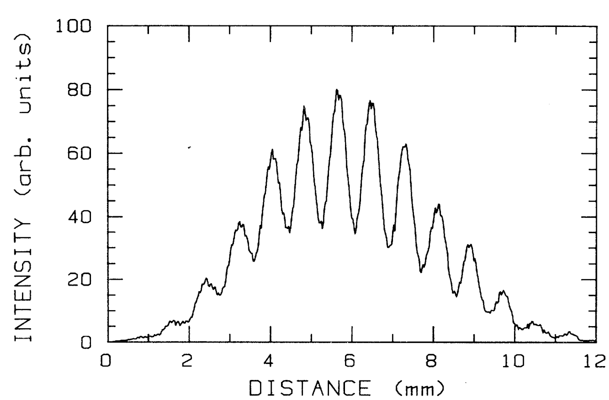

FIG. 3. Ensemble average of 272 shots with an average of 1.9 photons per mode in the signal input to the amplifiers. The measured visibility was 0.39.

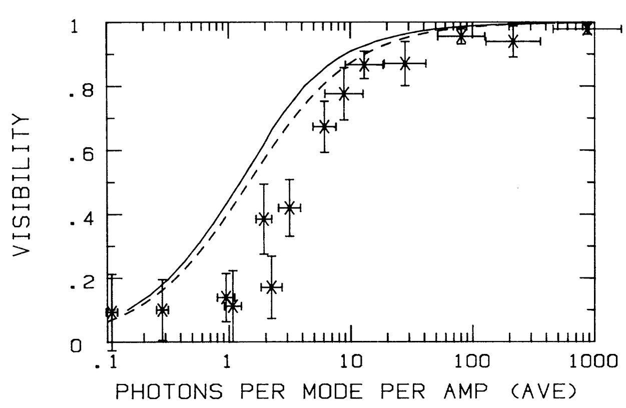

FIG. 5. Visibility as a function of the average number of photons per mode input to the Raman amplifiers in the interferometer plotted on a logarithmic scale. The dashed curve shows the theoretical results using an ideal, single-mode amplifier; the solid line indicates the results using the Raman theory. The theoretical curves fall somewhat below a visibility of 0.5 with an average of one photon per mode input because the beam splitters did not have a 50/50 transmission/reflection ratio.

each amplifier [18]. To determine an approximate number of modes, we took the ratio of the gain-narrowed Raman linewidth to the pump linewidth [19]. This is plotted in Fig. 5 on a logarithmic scale. As in Fig. 4, the theoretical results from the full quantum theory for Raman amplification are shown as a solid curve. In addition, the calculation for ideal, single-mode amplifiers are shown as a dashed curve. This curve was calculated from Eq. (2) at high gain using the experimentally measured values for $T_{\rm bs}$, $R_{\rm bs}$, and $T_{\rm po}$.

In Figs. 4 and 5 the experimental results clearly lie below the theoretical results. One of the possible explanations for this is that not all of the Stokes signal input photons were amplified, due to lineup difficulties and scattering losses. To account for these losses theoretically, we replaced the term $\langle \hat{b}_G^\dagger \hat{b}_G \rangle$ in Eq. (2) with $\alpha \langle \hat{b}_G^\dagger \hat{b}_G \rangle$, where α indicates the fraction of input signal that was amplified. With this alteration, Eq. (2) best fitted the data when $\alpha = 0.6$. Thus a 40% loss of input signal would account for the discrepancy between theory and experiment.

In conclusion, both the theoretical and experimental data in Fig. 5 indicate that it takes very few photons per mode to observe large visibilities, or put another way, only a few photons per mode are required to dominate the noise. This experiment explicitly demonstrates that the amplified field retains some "memory" of the phase of the input signal, even with extremely small inputs. Previous work has shown that the Raman amplifier can operate at the quantum-mechanical limit [20]. The similarity in results between the Raman theory and the ideal, single-mode amplifier theory reinforces this conclusion, and the experimental results show that the quantum-mechanical limit can be approached in practice.

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[10] This experiment is very similar in principle to Young's double-slit experiment with separate amplifiers behind each slit discussed in Ref. 1.

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[15] The fully quantum-mechanical model of Raman scattering can be written in the form of an ideal linear amplifier with multiple modes [P. R. Battle, R. C. Swanson, and J. L. Carlsten, Phys. Rev. A (to be published)]. Thus, except for the complications associated with the multiple modes, one would expect the Raman system to give results very similar to those given by the ideal, single-mode amplifier.

[16] The diode spacing in the linear diode array was 25 μm, providing good resolution for the fringes measured.

[17] In a separate experiment measuring the output of the Raman generator with a photomultiplier tube, we found that the gain [W. K. Bischel and M. J. Deyer, J. Opt. Soc. Am B **6**, 677–682 (1986)] had to be reduced by 12% for theory to agree with experiment. This reduced gain was used to obtain the theoretical results presented in this Letter.

[18] The average number of photons input to the amplifiers was taken to be one-fourth the average number of photons input to the interferometer. Since in our experiment $T_{\rm bs} = 0.78$, $R_{\rm bs} = 0.22$, and $T_{\rm po} = 0.5$, one calculates that there were actually more photons than this input to the lower amplifier in Fig. 1 and less photons than this input to the upper amplifier.

[19] The ratio of the Raman linewidth to the pump linewidth varied from 16.1 at very low gains in the generator to 4.4 at the gain corresponding to the farthest experimental data point to the right in Fig. 5. The gain narrowing of the Raman linewidth was calculated assuming the system was in steady state [K. Rzazewski, M. Lewenstein, and M. G. Raymer, Opt. Commun. **43**, 451–454 (1982)].

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