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Excess Quantum Noise is Colored

Abstract

We demonstrate both theoretically and experimentally that excess quantum noise is colored. The experiments were performed on a a miniature He-Xe gas laser, operating at 3.5 μm, with an adjustable nonorthogonality of the polarization modes.

Spontaneous emission is a fundamental source of noise in a laser. Usually, this quantum noise amounts to a level of "one photon per mode", leading for instance to the well-known Schawlow-Townes limit to the laser linewidth. Recently, there has been much interest [1, 2] in *excess* quantum noise, which appears when the eigenmodes of the laser resonator become nonorthogonal [3, 4]; the spontaneous emission noise has an apparent strength of "K photons in the lasing mode" in this case. The enhancement factor K can become quite large, $K \approx 500$ has been demonstrated in recent experiments, and the possibility of K values larger than 10^4 has been predicted [5]. This leads naturally to the question: what are the limitations to the concept of excess quantum noise?

We have demonstrated both theoretically and experimentally one such limitation, namely that excess quantum noise is spectrally colored [6]. This is in contrast to the usual spontaneous emission noise in a laser with orthogonal eigenmodes, which is essentially white noise. The coloring can be attributed to the finite time it takes for the excess quantum noise to build up from the "one-photon per mode" level. Thus, the picture of simply having "K noise photons in the lasing mode" breaks down.

The experiments were performed by measuring the intensity noise of a miniature He-Xe gas laser, operating at 3.5 μm, with an adjustable nonorthogonality of the polarization modes [7]. The theory of the coloring of excess quantum noise applies here in its simplest form, since a two-mode description is sufficient. A typical result is shown in Fig. 1, together with the theoretical prediction. The coloring of the excess noise factor is clearly visible, and the agreement with theory is excellent. Clearly, the maximum value of K is only reached for zero frequency, and the excess noise disappears ($K = 1$) for high frequencies. The coloring bandwidth was typically a few megahertz in our experiments (1.1 MHz in Fig. 1). This corresponds to the time scale on which the polarization-modifying elements in the laser resonator convert polarization-angle fluctuations into excess intensity fluctuations.

The origin of excess quantum noise, including the coloring, can be conveniently explained using a geometrical picture, illustrated in Fig. 2. It shows two nonorthogonal eigenmodes (the

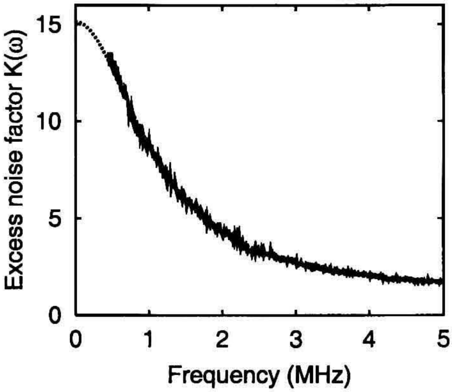

Figure 1: Demonstration of the coloring of excess quantum noise. The solid line is the experimental data, normalized intensity noise of a HeXe gas laser having nonorthogonal polarization modes. The dotted line is the theoretical prediction.

lasing mode and a nonlasing eigenmode) as vectors in the state space describing the optical field in the resonator. In the case of our experiments on nonorthogonal polarization modes, these vectors can be thought of as simply representing the direction of (linear) polarization of the light in the laser resonator. Spontaneous emission that is directly emitted into the polarization direction of the lasing mode contributes the usual "one photon per mode" to the laser noise. More interesting is what happens to spontaneous emission that is emitted in a direction orthogonal to the lasing eigenmode, as depicted in Fig. 2. This is equally likely to occur, since spontaneous emission will be isotropic in polarization direction. For orthogonal eigenmodes, these spontaneous emission events do not contribute to noise in the lasing eigenmode. In contrast, they are important for nonorthogonal eigenmodes. The time evolution of such a spontaneously emitted photon can be visualized by decomposing it into the separate components along the two eigenmodes, as indicated by the dashed lines. Each of these components will evolve according to the eigenvalue of the corresponding eigenmode. Hence the component along the nonlasing eigenmode (which has a net loss compared to the lasing mode) will rapidly decay, and only the component along the lasing eigenmode, labeled as "excess noise" will remain. Thus, spontaneous emission in a direction orthogonal to the lasing eigenmode will evolve into noise in the lasing eigenmode, with a strength corresponding to "$K-1$ photons". The timescale for this to occur is the decay rate of the nonlasing mode, and this is what sets the timescale for the coloring.

We are currently further exploring the limitations to the concept of excess quantum noise. Our results indicate that several other mechanisms can limit the amount of excess noise observed. Examples include the anisotropy of the gain saturation and the case that the excess quantum noise becomes so strong that it can no longer be treated perturbatively. In addition, we have studied the effects of mode-nonorthogonality on other fundamental sources of laser noise, such as the Poissonian pump noise.

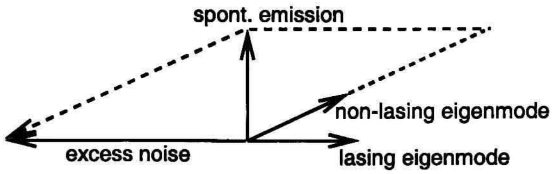

Figure 2: A geometrical representation of nonorthogonal eigenmodes, and the origin of excess quantum noise. This geometrical picture can also be used to explain the coloring of excess quantum noise.

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