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Detection of weak signals via the decay of an unstable state: Initiation of an injection-seeded laser

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We have demonstrated the detection of weak optical signals via the decay of an unstable state. A Q-switched laser is an example of an unstable state, the decay of which has to be triggered either by quantum fluctuations or by an injected external signal. Measurement of the initiation time of the laser intensity allows us to determine the strength of the external signal with a dynamic range of 7 orders of magnitude. It is possible to detect signal levels that correspond to less than one photon in a selected cavity mode.

The decay of unstable states has long been a paradigm in statistical physics[1]; it represents diverse phenomena such as spatial pattern formation in Rayleigh-Benard convection,[2] spinodal decomposition,[3] and the quantum initiation of laser radiation.[4,5] A Q-switched laser is a typical example of an unstable state; the decay of such a state has to be initiated by quantum fluctuations or by an external injected signal.

In this paper, we demonstrate for the first time the detection of very weak optical signals via the decay of an unstable state. The effect of the injected signal is a reduction in the time of decay of the state; the measurement of the signal intensity is thus converted to measurement of the initiation time. The initiation time is defined here as the time taken for the order parameter (e.g., the electric-field intensity) to reach a specified fraction (2%) of its steady-state magnitude. It is shown that signal levels that correspond to less than one injected photon on the average in the cavity mode (tuned to the external signal frequency) can be detected. A dynamic range of detection of at least 7 orders of magnitude, high-resolution bandwidth (≈ 5 MHz), and wide-range tunability are characteristic of this technique. Good agreement between theory and experiment is obtained.

A brief review of previous work is necessary to put our work in perspective. In our previous experiment (Ref. 4) we studied the passage time statistics of a dye-laser initiation from a spontaneous-emission background; no injected signal was present. The main emphasis was to disentangle the effects of quantum and pump noise. Arecchi, Meucci, and Roversi[5] have studied the initiation statistics of a CO_2 laser by very similar techniques, and made the important distinction between the effect of the initial number of noise photons and the "noise along the path." They determined the initial mean-noise photon number in their laser to be ≈ 1500. In a dye laser we find that the contribution of noise along the path is negligible. Mecozzi *et al.*[6] have studied the passage time statistics of a semiconductor laser, while Lefevbre *et al.*[7] have performed a study of transients in far-infrared lasers. The experiment reported here demonstrates a novel technique for the detection of weak injected coherent signals via the decay of an unstable state.

The equation often used for a description of the decay of an unstable state is

$$dz/dt = az - A|z|^2 z + q\,, \tag{1}$$

where z is a macroscopic order parameter; it may be regarded as the amplitude of the radially varying velocity field for fluids and the complex electric field for a laser. For fluids, $a=(R/R_c^\infty)-1$, where $R=R_c^\infty$ is the Rayleigh number that corresponds to the convective threshold,[2] while for lasers it is the net-gain coefficient.[4] The coefficient A leads to the saturation of the order parameter. Together, these coefficients determine the transient and steady-state behavior of the system. The spatial dependence of the order parameter has been neglected; this approximation is very well justified in the case of lasers, and also under certain conditions for fluid systems.[2]

The additive term q on the right-hand side of Eq. (1) is necessary to initiate the growth of the order parameter z and may be either stochastic, a constant, or a combination of both:

$$q(t) = \kappa_e E_e + \tilde{q}(t)\,. \tag{2}$$

E_e and κ_e are the external field and its coupling coefficient, while the noise source $\tilde{q}(t)$ represents spontaneous emission fluctuations. The size of the injected field or the strength of the noise source may be microscopic in comparison to the final steady-state value of z.

The decay of an unstable state is often illustrated by the example of a particle falling off the top of a potential hill.[1] The descent of the particle from the top of the hill must be triggered by some source of disturbance. A stochastic noise source on the right-hand side of Eq. (1) corresponds to a random force that initiates the fall of the particle. A small additive constant would also serve to initiate the descent. In this experiment both a stochastic noise source (spontaneous emission) and an additive constant (the injected signal) contribute to triggering the growth of the field. It is shown below that from measurements of the initiation time of the laser intensity the magnitude of an injected signal can be determined with a large dynamic range, limited here by the strength of the spontaneous emission into the cavity mode. This technique of so-called "super-regenerative" detection of weak external signals was widely used in radar detectors.[8] We demonstrate here the operation of a super-regenerative receiver in the optical regime; the theoretical basis for the experiment was examined earlier.[9]

Our experiment was performed with an argon laser pumped single-mode tunable ring dye laser (which served as the receiver) and a polarization stabilized He-Ne laser that was used as the source of the injected signal. The experimental arrangement is shown in Fig. 1. The dye laser has a cavity length of 1.55 m and is operated unidirectionally by means of an optical diode (Faraday rotator and quartz compensator). Coarse tuning is achieved by a birefringent tuner while precise control of the wavelength is obtained through the use of a thin and thick etalon. An iris is inserted in the cavity to allow only the Gaussian zeroth-order transverse mode to lase in the steady state. The cavity loss was estimated to be 13% with an acousto-optic modulator (AOM 1) inserted into the cavity. The AOM is used to Q switch the laser for the measurement of the initiation time of the radiation. The He-Ne laser beam is injected into the dye-laser cavity, and serves as the external signal that seeds the growth of the dye-laser cavity mode. A second AOM (AOM 2) splits the He-Ne beam into zeroth-order and first-order beams. The former is injected into the dye-laser cavity, and is roughly mode matched ($\approx 10\%$ efficiency) with a telescope. With no attenuation, an injected signal level of 7.7 μW of He-Ne power (with no attenuation) was estimated to be in the cavity mode of the dye laser. The level of the injected signal intensity can be attenuated by many orders of magnitude with suitable neutral density filters. An optical isolator prevents feedback of reflected light into the He-Ne laser, so that its frequency stability is maintained. An acousto-optic modulator with a rise time of 0.27 μs was used to Q switch the laser on and off in response to a step function wave form from a pulse generator. The dye laser was tuned as accurately as possible with a wave meter. Beats between the dye laser and the first-order diffracted He-Ne laser beam (shifted 80 MHz to avoid $1/f$ noise) were observed on a radio frequency spectrum analyzer. A quantitative measure of the detuning between the dye laser and the signal mode of the He-Ne laser was thus obtained. The dye-laser beam was incident on a fast photodetector and the Q-switched transients were recorded on a digital oscilloscope with a resolution of 100 ns and stored on disk by the microcomputer. The digital oscilloscope was triggered after a logical AND was performed between the filtered (1-MHz bandwidth) output of the spectrum analyzer and the pulse generator. This special triggering capability allowed us to investigate the effect of detuning between the dye laser and the He-Ne laser on the initiation time of the radiation. For a given detuning, it also allowed us to reject trajectories for which the dye-laser frequency deviated beyond the specified limits.

The initiation time was defined in our experiment as the time for the intensity to reach 2% of its steady-state value. Figure 2 illustrates the measured initiation times versus the attenuation of the He-Ne laser-beam intensity. A clear logarithmic dependence is evident over the entire range except for the very highest attenuations. The initiation time for the laser from a spontaneous emission background is seen to be about 12.5 μs. As the strength of the injected signal is increased, the initiation time decreases to 2.3 μs. The data was taken at an excitation level of the laser of about 5.2% above threshold. Fifty trajectories of the dye-laser intensity were averaged to obtain the initiation times plotted in Fig. 2.

A comparison of the experimental results with theoretical calculations is also shown in Fig. 2, where the solid line has been obtained from numerical simulations of a sto-

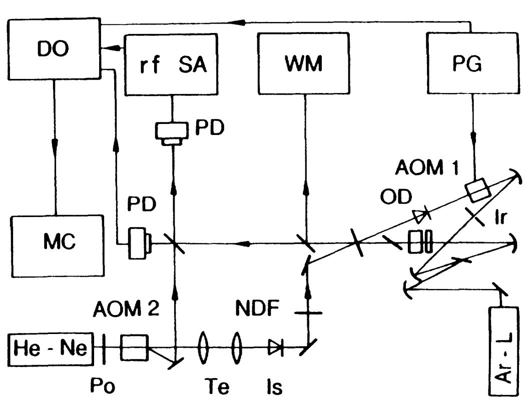

FIG. 1. Experimental arrangement for the detection of signals via the decay of an unstable state. Ar-L, argon laser; Ir, iris diaphragm; OD, optical diode; AOM 1, AOM 2, acousto optic modulators; PG, pulse generator; WM, wave meter; NDF, neutral density filter; Te, telescope; Is, optical isolator; rf SA, radio-frequency spectrum analyzer; PD, photodiode; Po, polarizer; He-Ne, helium neon laser; MC, microcomputer; DO, digital oscilloscope.

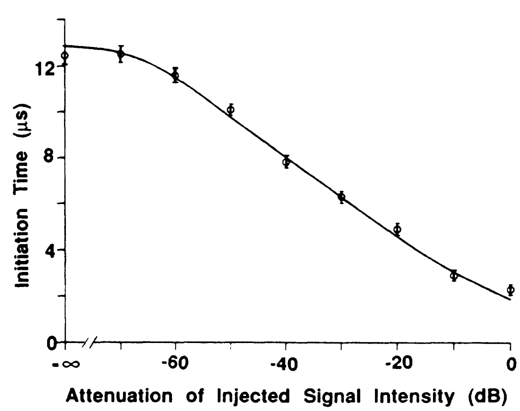

FIG. 2. Initiation time of the laser radiation vs the attenuation of the injected signal intensity. The solid line is obtained from stochastic simulations of the laser model with parameter values obtained from experiments. The dye laser and He-Ne laser are tuned to resonance with each other. The error bars are due to technical limitations on all but the first point, where the intrinsic uncertainty is comparable.

chastic model[9] for the growth of the laser field. The sensitivity predicted by the theory with parameters appropriate for the dye-laser detector has been achieved in our experiment. The response of the Q-switching AOM was included in the computation, and the net gain, saturation, and noise strength parameters were estimated from the experimental data or taken from previous experimental measurements.[4] The inclusion of the finite response time of AOM 1 was important in calculating the shorter initiation times; more complicated examples of such delayed bifurcations have been studied previously.[10,11]

It is interesting to estimate the average number of photons within the cavity mode that we are able to detect by this technique. From Fig. 2, the threshold of detection is found to be approximately 7 pW, which corresponds to an average photon number of about 0.2 in the cavity mode. This power level is comparable with the estimates for the spontaneous-emission background-noise power in the cavity mode as well.

The dependence of the initiation time for the dye laser on detuning with respect to the He-Ne laser was also investigated. This dependence is shown in Fig. 3, and illustrates the bandwidth resolution of the receiver. The circles are the experimentally measured initiation times for a constant injected external signal. The solid line was obtained from stochastic simulations of the equation

$$dE/dt = (a - i\Delta\nu)E - A|E|^2E + \kappa_e E_e + \tilde{q}(t) , \qquad (3)$$

where the detuning $\Delta\nu$ between the dye and He-Ne lasers is now included in the model.[12] The values of the parameters are the same as in Fig. 2. Good agreement between experiment and theory is obtained. The possible asymmetry indicated in the experimental measurements could be due to an asymmetry in the loss profile of the laser. An estimate for the receiver bandwidth is ≈ 5 MHz. Thus, it is clear that only signals within an extremely narrow range of frequencies will influence the growth of the laser radiation. The presence of background radiation at other wavelengths will have a negligible influence on the performance of this detector. At the same time, the tunability of the dye laser provides the capability of operation over a wide range of wavelengths.

The initiation time will also depend on the statistics of the injected signal. In this experiment the injected signal was coherent. It is necessary to account for the fluctuations in the injected signal if they are significant on the time scale of detection. The measurement of initiation-time statistics will then be important. A study of this issue is now in progress, and will be addressed in a future publication.

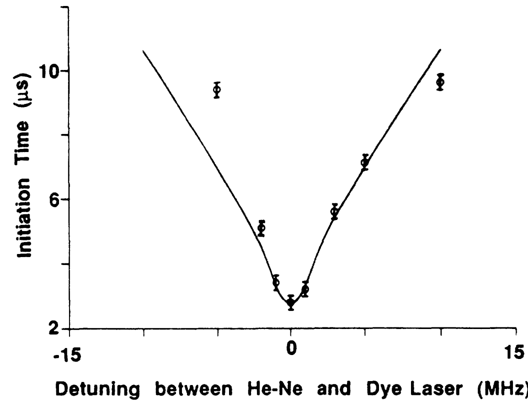

FIG. 3. Detuning dependence of the laser initiation time. The circles are experimental measurements, while the solid line was obtained from stochastic simulations.

In conclusion, we have demonstrated the operation of a highly sensitive, high-resolution receiver in the optical wavelength range based on the decay of an unstable state. The measurement of a signal strength is converted to the measurement of a time interval. The sensitivity of this detection procedure is due to the regenerative amplification of the signal beam in the gain medium. The time taken for the intensity to reach a fraction of the steady-state intensity provides the quantitative measure of the strength of the incident signal. The large dynamic range of the detection scheme is due to the logarithmic dependence of the initiation time on the strength of the injected signal. Applications of this detection technique may range from astronomy to radar receivers[13,14] and the technique should be applicable to other physical systems, such as fluids, that are described by a similar mathematical framework and provide information on random and systematic forces that initiate the decay of an unstable state.

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