NONLINEAR DYNAMICS OF BROAD-BAND LASERS

PROGRESS REPORT

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List of Publications

1. "Instabilities and chaos in a multimode, standing-wave cw dye laser," I.A.McMackin, M.Beck, C.Radzewicz, and M.G.Raymer, Phys. Rev. A **38**, 820 (1988).
2. "Strong-field dynamics of a multimode, standing-wave dye laser," M.G.Raymer, Z.Deng, and M.Beck, J.Opt.Soc.Am. B5, 1588 (1988).
3. "Transition from quantum-noise-driven dynamics to deterministic dynamics in a multimode laser," M.Beck, I.McMackin, and M.G.Raymer, Phys. Rev. A **40**, 2410 (1989).
4. "Conical Emission from a micro-cavity dye laser," S. Hodges, W. Gadomski, and M.G. Raymer, Proceedings of the 1990 International Quantum Electronics Conference, May 1990.
5. "Conical Emission from a micro-cavity dye laser," S. Hodges, W. Gadomski, and M.G. Raymer, submitted for publication, Mar. 1990.
6. "Dynamics of Multimode, Short-Cavity Dye Lasers," W.Gadomski, S.E.Hodges, and M.G.Raymer, Proceedings of Nonlinear Dynamics in Optical Systems. June,1990.

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ABSTRACT

Significant progress has been made in several areas. The source of mode-intensity fluctuations in a three-mirror, multimode dye laser has been identified in the typical operating regime well above threshold. It was found experimentally that deterministic four-wave mixing interactions are the underlying cause. We have also made new theoretical studies concerning the regime just above threshold and predicted that the mode fluctuations will be dominated by quantum noise in this regime. We have constructed a preliminary-design short-cavity dye laser in an attempt to enhance this quantum effect, and are now beginning to characterize its output. We have also constructed a Ti:Sapphire laser, and are beginning its study.

V. Results of Previous DOE-Sponsored Research

A. Three-mirror dye laser

A standard three-mirror-cavity dye laser, similar to those commonly used in ILS, was studied and the results were reported in Ref.[1], which formed the basis of Ian McMackin's PhD thesis at the University of Rochester. It was found that deterministic four-wave-mixing interactions are responsible for the apparently random fluctuations of mode intensities in this type of laser. This contradicted the basic assumptions of many researchers who assumed that quantum noise was responsible.

B. Theory of laser mode fluctuations

In Ref.[1] we also carried out numerical simulations of the multimode dye laser, and found semi-quantitative agreement with the experiment. The model is based on third-order, coupled-mode, laser theory, including 31 longitudinal modes, population oscillations and spatial hole burning. These equations of motion are well known, but had not been previously solved. If the electric field is expanded in a set of standing-wave spatial modes, as

$$E(z,t) = \sum_n E_n(t) \sin(k_n z) \quad (1)$$

then the form of the equations of motion for the mode amplitudes $E_n(t)$ is given by:

$$\frac{d}{dt} E_n = -\gamma_n E_n + g_n E_n \left[1 - \sum_m C_{nm} |E_m|^2 \right] + g_n \sum_{l \neq n} \sum_m D_{nml} E_l E_m E_{m+l-n}^* + F_n(t) \quad (2)$$

where γ_n is the cavity decay rate, g_n is the gain coefficient, C_{nm} is a mode competition coefficient, D_{nml} represents mode coupling by four-wave mixing, and $F_n(t)$ is a delta-correlated noise term representing spontaneous emission. Note that the molecular polarization and

population have been adiabatically eliminated, since their decay times are much shorter than those of the field modes ("Class A" laser).

By solving these equations numerically we found that the fluctuations can arise through deterministic mode coupling, in agreement with the experiment. The mode-intensity correlation time can be obtained from solutions of this kind. The correlation time was found to decrease with pump power and the agreement with experiment is quite good. On the other hand, it would be interesting to find out in which operation regime, if any, the quantum noise terms are important.

To this end we recently solved Eq.(2) numerically with all terms retained. [2] The result for mode correlation time versus power is shown in Fig.1. At high power the correlation time is seen to decrease, in agreement with the experiment, while at low power it increases, in agreement with the rate-equation theories without four-wave mixing, represented by the dashed line.

Fig.1 Correlation time of individual mode intensity.

This provides an interesting insight into the factors that control the correlation time, which should be maximized for ILS applications. At low powers the smallness of the field amplitudes makes the four-wave mixing terms, which are cubic in field strength, negligible, allowing the quantum noise to dominate. At high powers the opposite is true and the

deterministic dynamics dominates. Thus, we have made a prediction concerning the upper bound on the correlation time. This may be the understanding we are looking for regarding the ultimate sensitivity of ILS. According to Fig.1 the maximum correlation time in a typical three-mirror dye laser occurs at about 0.1% above the laser threshold. Unfortunately, it is difficult to operate lasers this close to threshold because of cavity vibrations and pump power fluctuations. The Renewal Proposal suggests ways to solve this problem.

C. Short-cavity dye laser

We have designed and constructed a dye laser with cavity length that is adjustable from 50 μ m to a few mm, and from 1cm to 10cm. In this laser we expect to see enhanced quantum noise effects.

This laser is operational and we are now attempting to stabilize its cavity in order to make quantitative measurements of its mode dynamics close to threshold.

D. Conical emission from short-cavity lasers

An unexpected spatial distribution of the output of the short-cavity laser has been observed. Intense, sharp rings were found surrounding the usual lasing spot. In the case of a cavity with plane-parallel mirrors, the rings were found to be at angles expected for a Fabry-Perot interferometer if the frequencies are those of the longitudinal cavity modes. That these frequencies are those occurring in the rings was verified by use of a monochromator. It appears that light in the lasing longitudinal modes is being scattered by something (mirrors, dirt, dye) inside the cavity and are constructively interfering only at the observed angles. It is not clear if the rings are lasing or just scattering passively. A conical laser emission similar to this was predicted in a famous paper by Kastler in 1962, but no observations have been reported. [3]

While our observation is new and interesting, it is not yet clear whether the conical emission affects in a significant way the mode-intensity dynamics in short-cavity lasers, which are of interest here. This will be explored further.

E. Ti:Sapphire laser

We have designed and constructed a Ti:Sapphire laser, consisting of a Ti:Sapphire crystal in a three-mirror cavity, pumped by an argon-ion laser. Ti:Sapphire is an interesting new laser material that is receiving attention for its wide tunability in the near IR at room temperature.

Ti:Sapphire lasers are good candidates for ILS as well as fundamental studies of instabilities.

References

1. I.A.McMackin, M.Beck, C.Radzewicz, and M.G.Raymer, Phys. Rev. A **38**, 820 (1988).
2. M.Beck, I.McMackin, and M.G.Raymer, Phys. Rev. A **40**, 2410 (1989).
3. A. Kastler, Appl. Opt.**1**,17(1962).

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