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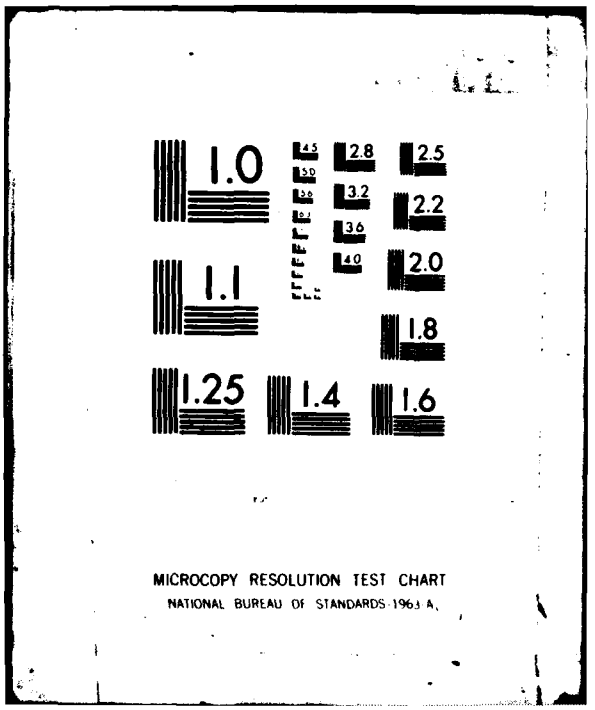
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COMPETITION EFFECTS IN LASERS

L. MANDEL (11)

PRINCIPAL INVESTIGATOR

FINAL REPORT

GRANT NO. AFOSR 81-0026
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This Final Report describes research carried out under the AFOSR Grant No. AFOSR 81-0026 during the one-year period October 1, 1980 to September 30, 1981. The first two-time photoelectric correlation measurements of a ring laser were completed during this period, which demonstrated the effect of mode competition in modifying the characteristics of a laser. Theoretical quantum treatments of a two-mode ring laser, and of a laser with coupled transitions were completed, and phase transition effects in a laser exhibiting optical bistability, and one with a saturable absorber, were investigated. The research resulted in four

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publications in the scientific literature, and 11 lectures describing various aspects of the research were presented at scientific meetings and research seminars. These are all listed in the Report.

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Abstract

This Final Report describes research carried out under the AFOSR Grant No. AFOSR 81-0026 during the one-year period October 1, 1980 to September 30, 1981. The first two-time photoelectric correlation measurements of a ring laser were completed during this period, which demonstrated the effect of mode competition in modifying the characteristics of a laser. Theoretical quantum treatments of a two-mode ring laser, and of a laser with coupled transitions were completed, and phase transition effects in a laser exhibiting optical bistability, and one with a saturable absorber, were investigated. The research resulted in four publications in the scientific literature, and 11 lectures describing various aspects of the research were presented at scientific meetings and research seminars. These are all listed in the Report.

1. Introduction

This is the Final Report on research carried out under the heading "Competition Effects in Lasers" during the period October 1, 1980 to September 30, 1981, supported by the AFOSR Grant No. AFOSR 81-0026.

During this one-year period four papers were published, or are now in press, in various technical journals as a result of the sponsored research. These are listed together with their abstracts in Section 3. This section also includes eight publications that were listed in the previous Final Report, but for which the complete references were then not available. Also during this period 11 lectures describing various aspects of the sponsored research were presented at scientific meetings and research seminars, and these are given in Section 4. One graduate student completed his Ph.D. degree during this period with partial research support from the AFOSR grant.

2. A Brief Review of Research Achievements

The first two-time photoelectric correlation measurements (Ref. 10) of a two-mode ring laser were carried out during this period. They demonstrated the effect of mode competition on the intensity fluctuations of the light intensity, and were in reasonable agreement with our earlier theoretical predictions. A more complete quantum treatment of the two-mode ring laser (Ref. 9), and of a two-mode laser with coupled transitions (Ref. 12) was completed. The theory of a laser with a saturable absorber was further developed (Ref. 11), and the phase transition associated with bistability effects in a two-mode laser was investigated (Ref. 9) over a very wide range of conditions.

3. Research Publications and Abstracts

The following papers were published or are now in press as a result of the research carried out under the AFOSR grant:

1. "Effect of Backscattering on the Behavior of a Dye Ring Laser", Rajarshi Roy and L. Mandel, Opt. Commun. 35, 247-248 (1980).

The effect of backscattering on the behavior of a dye ring laser is investigated by photoelectric counting measurements. It is found that there exist two laser regimes, a low backscattering regime in which the laser exhibits metabistability and random mode switching, and a high backscattering regime in which switching is suppressed. In the latter case the photon statistics are similar to those of a single-mode standing wave dye laser.

2. "First-Passage-Time Distributions under the Influence of Quantum Fluctuations in a Laser", Rajarshi Roy, R. Short, J. Durnin and L. Mandel, Phys. Rev. Lett. 45, 1486-1490 (1980).

The distribution of first-passage times is calculated for a homogeneously broadened two-mode laser, that is characterized by a bistable potential. As a consequence of quantum fluctuations, such a system tends to switch spontaneously between the two metastable states. The results of the calculation are compared with first-passage-time measurements of a two-mode dye laser.

3. "Complete Coherence in the Space-Frequency Domain", L. Mandel and E. Wolf, Opt. Commun. 36, 247-249 (1981).

An expression is derived for the general form of the cross-spectral density of a field that is spatially fully coherent, throughout some region of space, at some particular temporal frequency.

4. "Quantum Statistical Theory of the Ring Laser", Surendra Singh, Phys. Rev. A 23, 837-852 (1981).

A unified quantum treatment is presented for bidirectional two-mode ring lasers using the approach of Haken and co-workers. Equations of motion for the reduced density matrix of the field have been derived and used to study the fluctuation properties of the radiation field in different kinds of active media. The steady-state photon number distribution for an inhomogeneously broadened gas ring laser is derived. It is shown that for equal losses the relative fluctuations and normalized cross-correlation of the photon numbers approach values 1/3 and -1/3, respectively, for large excitations. For unequal losses the laser may emit typical single-mode laser radiation in the direction of the favored mode and typical equilibrium blackbody radiation in the direction of the weaker mode. Our results generally agree with the predictions of earlier treatments when the losses are equal. However, for unequal losses we predict different behavior for large excitations. Effects of detuning, spatial, and temporal variation of atomic inversion on the fluctuation properties have been investigated in the coherent-state diagonal representation of the density matrix, and steady-state intensity distributions have been derived for various kinds of active atoms. It is shown that for inhomogeneously broadened solid-state ring lasers spatial inhomogeneities may couple the modes strongly and the statistical properties of such lasers, characterized by a double-peaked intensity distribution and large relative-intensity fluctuations, may be similar to those of a homogeneously broadened ring laser. Curves are presented to illustrate the behavior.

5. "Intensity Correlation Time of an Optical Field",
L. Mandel, Opt. Commun. 36, 87-89 (1981).

A measure of the time for which intensity correlations persist in a stationary optical field, suitable for both classical and quantum fields, is proposed and illustrated by several examples.

6. "Carrier Frequency and Envelope of an Electromagnetic Wave",
L. Mandel, J. Opt. Soc. Am. 71, 362-363 (1981).

Two commonly used envelope representations of an electromagnetic field are compared. The analytic signal representation is shown to be preferable in that it leads to a more slowly varying envelope.

7. "Optical Bistability Effects in a Dye Ring Laser",
L. Mandel, Rajarshi Roy and Surendra Singh, in Optical Bistability (1981), eds. Charles M. Bowden, Mikael Ciftan and Hermann R. Robl (Plenum, New York, 1981) pp. 127-150.

The theory of a homogeneously broadened two-mode ring laser is discussed. Because the mode coupling constant can be twice as great as under conditions of inhomogeneous broadening, new effects like quasi-bistability appear, and the radiation field undergoes a phase transition near threshold that is of the first order. This is reflected in a double peaked probability distribution of each mode intensity, and in alternate switching of the excitation between modes. A first passage time calculation shows that the dwell times should increase rapidly with excitation. These predictions are tested by photoelectric counting and other measurements on a dye ring laser. Although the observed photoelectric counting distributions closely resemble the theoretical ones, measurements of the dwell times reveal significant discrepancies between theory and experiment, that are believed to be due to backscattering. The adequacy of a theory based on two-level atom modesl in accounting for the behavior of a dye ring laser is briefly discussed.

8. "Photoelectric Correlations and Fourth Order Coherence Properties of Optical Fields",
L. Mandel, in Optics in Four Dimensions-1980, eds. M.A. Machado and L.M. Narducci (American Institute of Physics, New York, 1981) pp. 178-195.

Photoelectric correlation measurements of optical fields are now becoming commonplace and, as is well known, they require fourth order correlation functions of the field for a description. Nevertheless, the fourth order theory of optical coherence has not received a great deal of attention. This is the subject of the present paper. When interference effects are combined with intensity correlations, we encounter correlation functions of the general form

$$\Gamma^{(2,2)} \equiv \langle V^*(\underline{r}_1,t_1)V^*(\underline{r}_2,t_2)V(\underline{r}_3,t_3)V(\underline{r}_4,t_4)\rangle \quad ,$$

which are functions of four space-time arguments. Some properties of such fourth order correlations, as they relate to interference and intensity correlation effects, are derived. The space arguments are generally suppressed in the calculation. The correlation functions are expressible as multiple Fourier transforms of certain fourth order spectral densities, which are functions of three frequencies in the stationary state.

(cont'd)

The superposition law for fourth order spectral densities is derived for independent light beams, and it is shown that the fourth order spectral densities exhibit the reproducing property under superposition only when the light obeys thermal statistics. Next the superposition law is found for the spectral densities of the photoelectric signals generated by light beams falling on photodetectors. Investigation of the photoelectric signal spectrum yields information on the spectrum of the light intensity fluctuations, and removes the measurement from the domain of optics to the domain of electronics. It is shown that the photoelectric spectral densities reproduce under superposition when the two light beams in question obey a certain factorization condition for second order correlations. Finally, it is shown that, under certain circumstances, all the relevant fourth order correlation properties of the optical field are expressible in terms of simpler two-frequency spectral functions.

9. "Correlations, Transients, Bistability and Phase Transition Analogy in Two-Mode Lasers",
F.T. Hioe and Surendra Singh, Phys. Rev. A, to be published (1981).

The general time dependent problem associated with a two-mode laser Fokker-Planck equation has been considered. Analytic expressions for the eigenvalues and the eigenfunctions have been derived for the below and above threshold operation of the system. It is shown that depending on the values of the pump parameters a_1, a_2 and the coupling constant ξ, a wide variety of dynamical behavior may be encountered. Thus for $\xi < 1$, interesting threshold effects may appear in the behavior of correlation times and linewidths as a function of excitation which may change their behavior whenever a mode passes through its threshold of oscillation. For $\xi = 1$ the correlation time of the stronger mode may pass through a maximum before it starts to decrease with increasing excitation. The weaker mode may show particularly interesting behavior for $\xi = 1$. Both the correlation time and the linewidth may approach a constant value independent of the excitation. For $\xi > 1$, the system may show bistability. Our analysis provides a deeper mathematical understanding of the onset of bistability and the analogy to the thermodynamic phase transition. Expressions for the switching time have been derived using several different procedures. We have also been able to derive closed form expressions for the two-time joint probability densities. It should be possible to test some of those predictions in photon counting experiments. Finally, we mention that our results and method should also be applicable in other similar problems, e.g., to the classical theory of coupled fields.

10. "Measurement of Two-Time Correlations in a Two-Mode Ring Laser",
Surendra Singh and L. Mandel, Opt. Commun., to be published (1981).

Photoelectric counting and two-time correlation measurements of each of the two counter-propagating waves of a He:Ne ring laser have been carried out. The results show reasonable agreement with theory over a range of laser pump parameters from -12 to +2, but increasing departures at higher excitations. The departures are believed to be due to backscattering.

11. "Quantum Theory of a Laser with an Inhomogeneously Broadened Saturable Absorber",
Surendra Singh and Rajarshi Roy, Phys. Rev. A, to be published (1981)

We present a quantum theory of a laser with an inhomogeneously broadened saturable absorber which is valid even for high intensity operation and which accounts for quantum fluctuations of the laser intensity. Both on- and off-resonance operation are discussed for travelling and standing waves in the laser resonator. The results of the theory are shown to agree with expressions previously derived by others under various approximations. The results are expected to be experimentally verifiable by photon counting measurements on, for example, helium-neon lasers containing a neon absorber cell.

12. "Intensity Correlations in a Two-Mode Laser with Coupled Transitions",
Surendra Singh and M.S. Zubairy, Phys. Rev. A 23, 2507-2512 (1981)

Intensity correlations in a two-mode laser oscillating on two coupled transitions have been studied by means of the Fokker-Planck equation. It is shown that they can be expressed in terms of the eigenvalues and eigenfunctions of a one-dimensional Schrödinger-type equation. It is found that near threshold intensity correlations cannot be approximated by a single exponential. For moderately large excitations, however, a single exponential dominates. Approximate analytic expressions for large excitations have been obtained which show that the correlation time increases with increasing excitation.

4. Lectures and Papers Presented at Meetings

The following lectures dealing with the research were presented at various scientific meetings and research seminars:

1. "Investigation of Spontaneous Switching of a Two-Mode Laser",
Rajarshi Roy, R. Short, J. Durnin and L. Mandel, Optical Society of America meeting, Chicago, Ill., October 17, 1980.

2. "Intensity Correlations of a Ring Laser",
Surendra Singh, S.R. Friberg and L. Mandel, O.S.A. meeting, Chicago, Ill., October 17, 1980.

3. "Are Optical Photons and Atomic Quantum Jumps for Real?",
L. Mandel, Dept. of Electrical Engineering and Dept. of Physics Joint Seminar, Columbia University, New York, N.Y., October 31, 1980.

4. "Are Atomic Quantum Jumps Real?",
L. Mandel, Joint Colloquium of the Departments of Physics, University of Waterloo and University of Guelph, at University of Waterloo, Canada, November 6, 1980.

5. "Laser Phase Transitions",
L. Mandel, Joint Colloquium of the Departments of Physics, University of Waterloo and University of Guelph at University of Waterloo, Canada, November 7, 1980.

6. "Spontaneous Switching and Quantum Fluctuations in Homogeneously Broadened Lasers",
Rajarshi Roy, Department of Physics Seminar, University of Arkansas, Fayetteville, Ark., January 23, 1981.

7. "Laser Physics and Quantum Optics",
L. Mandel, Rochester Symposium for Physics Students, University of Rochester, Rochester, N.Y., January 24, 1981.

8. "Spontaneous Switching and Quantum Fluctuations in Homogeneously Broadened Lasers",
Rajarshi Roy, Seminar at JILA, University of Colorado, Boulder, Colo., February 18, 1981.

9. "Phase Transitions in the Laser",
L. Mandel, Department of Physics Seminar, University of Texas at Austin, Austin, Texas, May 11, 1981.

10. "Phase Transitions in the Laser",
L. Mandel, Laboratory for Laser Energetics Luncheon Talk, University of Rochester, Rochester, N.Y., May 15, 1981.

11. "Measurements of Two-Time Correlations in a He:Ne Ring Laser",
Surendra Singh and L. Mandel, Optical Society of America meeting, Kissimmee, Fla., October 28, 1981.

5. Personnel

The following people contributed to the research carried out under this grant:

L. Mandel, Professor of Physics, Principal Investigator
F.T. Hioe, Senior Research Associate
K. Kaminishi, Research Associate
J. Andersen, Research Assistant
J. Durnin, Research Assistant
S. Friberg, Research Assistant
P. Lett, Research Assistant
Rajarshi Roy, Research Assistant
R. Short, Research Assistant
Surendra Singh, Research Assistant
R. Andrus, Secretary

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