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ONR FINAL REPORT FOR CONTRACT #N00014-90-J1029

Murray Sargent III
Optical Sciences Center, University of Arizona, Tucson, AZ 85721
December 21, 1992

This contract started in October, 1989 and continued through March 1992, which included a half-year extension. The overall purpose of the contract was to investigate various aspects of the quantum theory of multiwave mixing with applications to squeezing in both atomic and semiconductor media. In the following seven sections, we briefly describe what we have achieved with help from the ONR contract in these and related areas. We also list the corresponding papers presented at meetings, the papers published in journals, and the work completed on two books.

1. Injected Atomic Coherence

In nonlinear spectroscopy and in laser theory, atoms are usually pumped incoherently, that is, any induced dipole moment is destroyed by the pumping process. Recently substantial interest in both micromasers and in correlated emission lasers has involved pumping in which induced dipoles are preserved. We have studied the effects of such injected atomic coherence on multiwave mixing processes and in a simple two-level laser. In particular, we have found that laser operation can occur way below the usual laser threshold and that below that threshold, the output field is always locked to the injected atomic coherence. While this result is pretty, we not that in general lasing without inversion is not particularly suprising. The gain is in the first instance proportional to the imaginary part of the induced polarization; with the right phase, you get gain. An inversion is only one way to ensure that you get the right phase, albeit a very good way.

2. Bichromatic and Local-Field-Correction Quantum Multiwave Mixing

The proposed work on bichromatic multiwave mixing was carried out analytically, but never reached publication, partly because some good work on part of the problem appeared, namely in resonance fluorescence. The corresponding squeezing coefficients (C_1 and D_1) still remain to be worked out in the literature.

We have worked out the quantum theory of multiwave mixing with local field corrections, including a first-principles derivation of the Maxwell-Bloch equations starting with a basic minimal coupling Hamiltonian in the Coulomb guage. This work will be submitted for publication in the first quarter of 1993.

3. Composite-Cavity Mode Laser

We have presented and published work on the composite cavity-mode approach to reflections by *a* external mirror. This reveals a very sensitive dependence on the length of the external cavity and might explain some experimental behavior that is currently attributed to chaos [see Rose *et al* (1992)]. This work is aimed an instability problems in semiconductor lasers, but the model should be useful for coupled lasers with two-level gain media as well.

4. Spectral Hole Burning and Population Pulsations in SCL Gain Media

This work studied hole burning and population pulsations in semiconductor gain media and related phenomena. We made substantial progress in this area, notably in being able to derive a general multiwave mixing formalism that treats the many-body quasiequilibrium semiconductor as well as simpler models with a unified notation. The trick was to express the mixing coefficients in terms of the single-mode susceptibility, which then encapsulates the model in question. This simple form reveals similarities and differences between multiwave mixing in a variety of media, and allows us to interpret the popular linewidth enhancement factor as the ratio of the imaginary to real parts of the mode coupling coefficient.

A related approach has enabled us to derive a multimode theory of the quasiequilibrium laser. This is limited to weak laser fields, but can describe the full many-body effects. Nevertheless, the theory is actually simpler than the original Lamb theory of the gas laser [see Sargent (1993)].

5. Quantum Multiwave Mixing in Semiconductor Laser Media

We have published a number of papers on the quantum theory of multiwave mixing in semiconductor media and found coherent-dip phenomena reminiscent of detuned two-level media with population-difference decay times (T_1) much larger than the dipole decay time (T_2). Some of this work has led to a more precise understanding of just when a simple two-level model has a chance of applying to a semiconductor and when it is likely to fail. As discussed in the SCL book and in the most recent OSA talk, the simplest two-band semiconductor model actually has four levels for each momentum-spin combination, two of which correspond to the two levels in a two-level system. Carrier-carrier scattering causes all four levels to have appreciable probability in a semiconductor gain medium. Hence it is dangerous to use a two-level model to describe even the simplest of semiconductors. It is particularly unwise, since a simple semiconductor theory often reduces to the solution of a few equations. Exceptions occur when the many-body effects of Coulomb enhancement and band-gap renormalization are included, or in the quantum theory of the semiconductor. One may curve fit some phenomena using such two-level models, since for small variations of parameters, the semiconductor characteristics are reasonably slowly varying that first and second-order Taylor series are good approximations.

6. Semiconductor Laser Photon Statistics

The SCL photon statistics is an important problem, since aside from the intrinsic interest about photon statistics, this area might help to explain the intensity squeezing observed by Yamamoto and others. The current theories are either based on a simple two-level model, or on circuit theory analogs. We have developed a joint photon/carrier-density statistics, p_{nN}, where n is the photon number and N is the carrier number. This approach leads to an intricate $2D$ set of equations. In the limit that the carrier number is exactly related to the photon number (via saturation), the two-dimensional space reduces to a one dimensional one similar to that for two-level media. In general, no such simple relationship exists in the semiconductor, since the saturation changes the chemical potential, which in turn changes the Fermi-Dirac distributions functions. These distributions are already traces over the original semiconductor-field probability functions, traces that destroy a simple relationship between semiconductor-field probabilities and a single photon number.

Nevertheless, we have recently found that the simple upper-to-ground-level two-level model predicts much of the thresholdless laser operation observed in laser diode structures that confine spontaneous emission to the laser axis.

7. Semiconductor Laser Linewidth

We have studied the SCL linewidth, including a complete derivation of the quantum-Langevin diffusion coefficients. This derivation will be given in our forthcoming book on *Semiconductor Laser Physics*. Several surprises have occurred, since noone seems that have done a first-principles derivation. Typically the diffusion coefficients reported in the literature were either adopted from the two-level theory or were intuited from circuit-theory analogs. At this point, the differences in the final answers do not appear to be large, and in any event have not been checked against controlled experiments.

8. Books

Much of the work related to semiconductor lasers has been incorporated into a draft of our forthcoming book W. W. Chow, S. W. Koch, and M. Sargent III, *Semiconductor Laser Physics*. With regard to books, we produced the second edition of the book *Elements of Quantum Optics*. This edition includes many new figures, corrections, and new sections on the relationship between four-wave mixing and photon echo, on light forces and atomic motion, and on the quantization of standing waves versus traveling waves. The first edition of this book was created with significant support from earlier ONR contracts.

Students and Post Docs supported

SungYuck An, Tim Carty, Mike Rose, Paul Gohman

Talks Presented

S. W. Koch, H. Haug, M. Sargent III, and N. Peyghambarian, "Optical Nonlinearities in Bulk and Quantum-Well Semiconductors and Semiconductor Quantum Dots," Fifth Interdisciplinary Laser Science Conference (ILS-*V*) (1989) (invited).

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