OPTICAL PROCESSES IN MICROCAVITIES

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OPTICAL PROCESSES IN MICROCAVITIES

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Preface

The quest for the next generation of computers with faster clock speed and increased memory as well as new, improved and higher bandwidth communication systems has led to a *photonics* technology, which incorporates optical sources, switches and interconnects into hybrid electronic circuits as an alternative to purely electrical technology. For example, optical fibers/waveguides and light are being substituted for wires and electrons, wherever practical, resulting in increased speed and higher transmission efficiency. Central to a number of photonic concepts is the *microcavity* which provides the feedback necessary for the generation and switching of coherent light. As cavities have been reduced in size from the familiar Fabry-Perot found in table top lasers, geometries have evolved in order to solve fabrication difficulties while maintaining high cavity Q. This has resulted in microcavity concepts which at first glance appear alien (see cover photos). In addition, new physical processes begin to dominate as the size scale approaches the wavelength of light and it is appropriate to consider the cavity a photonic confined system in analogy to quantum confined semiconductor systems (e.g. one, two and three dimensional microcavities being analogous to quantum-wells, -wires or -dots, respectively).

At reduced dimensions, modified spontaneous emission, squeezed states and chaos are readily observed. Enhanced spontaneous processes, in particular, promise ultralow threshold high speed lasers and efficient light emitting diodes have highly directed emission patterns. These processes, although associated with cavities, warrant fundamental investigations in their own right and are of importance to researchers in the fields of quantum optics, quantum electrodynamics, nonlinear optics, and chemical physics. The properties of leaky modes of such small cavities are also of intense interest to researchers in computational classical electromagnetics. In addition to photonics, microcavity concepts are key to several other important applications. For example, there are efforts underway to improve detection of airborne biological species by utilizing cavity enhanced spontaneous emission and to develop particle specific chemical diagnostics for atmospheric and combustion chemistry which utilize the optical feedback inherent within microdroplets to support stimulated processes.

Historically, much of the early research (e.g., Lorenz-Mie theory) on microcavities was first performed using liquid droplet systems, which are self-fabricating high Q resonators, in an effort to understand light scattering from clouds and colloidal suspensions. Indeed, cavity QED spectral features associated with cavity resonances were first observed in analogous solid microspherical and cylindrical cavities nearly 15 years ago. The semiconductor laser community has recently given this phenomena considerable attention as well in their efforts to fabricate ultralow threshold lasers. Because of the multidisciplinary nature of microcavity research, it is not uncommon for researchers in a given field to be unaware of the conceptual and technological advances pertaining to microcavities forged by researchers in other fields. Differences in terminology often make even key word searches ineffective. For example, the resonances of spherical microcavities are referred to in the literature by various names: whispering gallery modes (WGM's), morphology-dependent resonances (MDR's), quasi-normal modes (QNM's), structure resonances, partial-wave resonances, Mie resonances and ripple structure. Furthermore, the notation used to label the index of refraction as well as to specify the radial and angular properties of microspherical resonances has not been consistent and is confusing even to the experts.

In 1988 while the field of optical processes in microcavities was still relatively immature, Barber and Chang edited *Optical Effects Associated with Small Particles* as Volume One of the Advanced Series in Applied Physics. In 1990, Barber and Hill published *Computational Light Scattering*, as Volume 2 of the same Series which serves as an invaluable aid for readers who want to compute the electromagnetic fields and resonances of cylindrical, spherical, and nonspherical micro-objects. In 1995, we felt that the field of optical processes in microcavities has markedly matured and is actively diversifying. In order to bind together experts with differing interests and to encourage new research into the exciting field of optical processes in or near microcavities, both of us thought it was timely to edit Volume 3 of the Advanced Series in Applied Physics.

In this Volume, we have asked eleven lead authors, all with widely different research interests, to write a chapter reviewing their important contributions to the common topic of optical processes in microcavities. Each of the lead authors and their co-authors have made seminal scientific advances in the fundamentals and applications of linear and nonlinear optical processes and electromagnetic interactions in micro-objects. We were most surprised that in spite of their many commitments, particularly to publish their new work in professional journals, ALL eleven lead authors immediately agreed to contribute a chapter. We are immensely pleased with the response, the tutorial nature of the content, the lucidness of the style, and last but not least, the fulfillment of the "on schedule" and "within the page limitation" requirements imposed by us on their chapters. The field of optical processes in microcavities is so active and large that we could have asked another eleven active lead authors to write a chapter reviewing their exciting and important findings. As the submission deadline drew near, we believe that many of the contributors to this Volume wished that other authors had been asked.

The lead chapter, by E.S.-C. Ching, P.-T. Leung and K. Young at the Chinese University of Hong Kong, is intended to be tutorial and serve as an introduction to the rest of the Volume. It treats microcavities as a mesoscopic and open (leaky) system and introduces, both physically and mathematically, the concept of quasi-normal modes (QNM's). Chapter One elegantly develops the notion of density of states, generalizes the Fermi golden rule to dielectric microspheres, and presents a time-independent perturbation theory to calculate the frequency shifts and the broadening of QNM's of a slightly distorted microsphere.

Chapter Two, by S. Brorson of TeleDanmark Research and P. Skovgaard of University College Cork, Ireland, introduce the reader to the "mode counting" method of estimating cavity quantum electrodynamic (CQED) modified emission rates. Mode-counting is a rigorous yet simple method of performing such estimates that straightforwardly sums the available modes of a cavity over a spherical surface in k -space. Cavity configurations offering various degrees of confinement from parallel planar-mirror to waveguide are considered. Experimental results are reported, demonstrating spontaneous emission lifetime changes when the radiating Er^{3+} ions are embedded within a gold coated optical fiber.

Chapter Three, V. Lèfevre-Seguin, J. Knight, V. Sandoghdar, D. Weiss, J. Hare, J. -M. Raimond and S. Haroche at Ecole Normale Supérieure, presents experiments performed on highly transparent silica microspheres, which can support whispering gallery modes with Q factors in the range of 10^9 - 10^{10} . Details relating to their impressive experiments on the splitting of the two-fold degeneracy of the clockwise and counter-clockwise circulating WGM's are reviewed. Also presented are details of

their experiments of direct mapping of the WGM's with a moveable fiber tip, much akin to near-field microscopy. Future use of these high-Q glass microspheres for CQED studies are proposed.

Chapter Four, by M. Barnes, C-Y. Kung, W. Whitten and J. M Ramsey at Oak Ridge National Laboratory and S. Arnold at Polytechnic University, considers CQED modified emission lifetime when the fluorescent dye molecule has a dynamic spectral broadening because of solvent interactions. The spectral broadening is typically much larger than the cavity resonance width. Consequently, the problem of CQED for molecules in condensed dielectric material is much more complicated than that of atoms in the gas phase. It is shown that microdroplets, because of the increase in the saturated absorption rate and the average fluorescence yield, make an excellent medium for single molecule fluorescence detection.

Chapter Five, by A. J. Campillo, J. D. Eversole and H-B. Lin at the Naval Research Laboratory, reviews CQED in microdroplets, particularly enhancement of the spontaneous emission in linear optical processes as well as the stimulated gain in nonlinear optical processes. Elegant experiments quantifying the CQED enhancements are presented. Such gain enhancements have enabled the remarkable demonstration of low-power cw nonlinear optical phenomena, such as stimulated Raman scattering, stimulated Rayleigh-wing spectral super broadening, and four-wave parametric oscillation. Review is made of the tour *de force* experimental procedures for generating ultra-stable droplets and uniquely identifying microcavity modes. Details are provided that pertain to determination of the Q factors, not through the spectral line width of the resonance peaks, but from the intensity decrease upon addition of an absorbing dye.

Chapter Six, from the joint efforts of M. Mazumder and R. K. Chang at Yale University, D. Chowdhury at Corning Research, and S. Hill at the Army Research Laboratory, develops an effective-average model that extends the often used concept of modal gain or loss in the field of semiconductor waveguides, to the case of a dielectric microsphere. With a new definition of mode volume, it is shown that on or near a resonance, a microsphere can be approximated as a closed cavity. The usual first-order perturbation theory for a closed cavity is then used to compute the effective-average gain or loss and the resonance frequency shift. Dispersive and absorptive optical bistabilities in a dielectric microsphere are modeled by using the effective-average and a time-independent perturbation method described in Chapter 1. A brief review of experiments with lasing microdroplets that are perturbed by size changes, shape distortions, and temperature-dependent changes in absorption, is presented. The perturbed spectra can provide information on droplet properties, such as evaporation rate, shape deformation, surface tension, and temperature.

Chapter Seven, by R. L. Armstrong at New Mexico State University, reviews the similarity between the nonlinear optical spectra from microcylinders and that from microdroplets. Specifically reviewed are MDR assisted lasing and stimulated Raman scattering from a micron-sized liquid cylinder, which serves as an example of a two dimensional microstructure. Spectral changes and emission time delays are discussed. Interesting changes occur in the MDR-related lasing spectra from layered dye-doped droplets and from droplets seeded with much smaller-sized fluorescent particles. When small latex particles, acting as scatterers, are placed in microdroplets, the suppression of lasing and SRS at wavelengths corresponding to higher Q MDR's and the increase in the pump-intensity threshold are noted.

Chapter Eight, by S. Arnold, S. Holler, and S. D. Druger at Polytechnic University, describes the role of the MDR's in efficient energy transfer between of molecules within microspheres. In an electrodynamically levitated microdroplet, the energy exchange between an excited donor and an unexcited acceptor is found to be enhanced at MDR's. Such energy transfer enhancement is more than a factor of 100 over the conventional near-field Förster transfer. The much longer range MDR-related energy transfer is confirmed by the striking differences between the donor-fluorescence and the acceptor-fluorescence images. Clearly, the MDR-related energy transfer can take place over the full circumference of the microparticle.

Chapter Nine, by R. E. Slusher at AT&T Bell Laboratories and U. Mohideen at the University of California at Riverside, reviews their research on semiconductor microdisk laser resonators, which are only a few microns in diameter and a few tenths of a micron thick. In this microstructure, the lasing characteristics from the microdisks are dramatically modified. Nearly 20% of the spontaneous emission is captured into a single lasing mode. Clearly reviewed are topics such as: controlling spontaneous emission rates; anomalous laser line width behavior; the existence of well-defined threshold; and the effect on the nonequilibrium carrier dynamics resulting from the strong coupling of the emitted radiation to the microcavity modes.

Chapter 10, by S-T. Ho, D. Y. Chu and J-P. Zhang at Northwestern University and M-K. Chin at Nanyang Technological University, Singapore, is a tutorial on the interaction of radiation with strongly-guided two-dimensional and one-dimensional dielectric waveguides, which are referred to as photonic wells and wires, an analogy to electronic quantum wells and wires. The channeling of the spontaneous emission into the lowest-order cavity modes modifies the lasing properties, because the spontaneous emission rates, as well as the spatial and spectral pattern of spontaneous emission, are significantly altered. Microdisk and photonic-wire lasers realized recently are reviewed and their novel applications in the future are proposed.

Chapter 11, by J. U. Nöckel and A. D. Stone at Yale University, presents the recent realization that chaos in classical dynamics can be related to the study of microcavity resonators, particularly asymmetric resonant cavities (ARC's). When the microcavity is asymmetrically deformed, the ray dynamics of the cavity modes becomes chaotic in the manner determined by the Kolmogorov-Arnold-Moser (KAM) theory of classical nonlinear dynamics. Without using the standard computationally intense electromagnetic techniques for large and highly deformed microstructures, this ray-optics model based on KAM theory, provides new physical insights. Detailed calculations can be performed readily on the degradation of the Q factors and the occurrence of directionality of the "escaped rays" from a highly deformed resonator. For the first time, specially designed ARC's can be conceived which combine the advantages of microdisks or microsphere cavities with the directional emission found in Fabry-Perot resonators.

We wished to express our sincere appreciation to Ms. Patricia Brodka at Yale and Ms. Anne Townes at NRL for all the administrative help they have cheerfully and expertly provided since the time we first thought about editing this Volume. We also wish to thank Dr. You-Huan Yeo at World Scientific Publishing Company for his assistance and encouragement.

Richard K. Chang

Anthony J. Campillo

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