CONTROLLING STEADY-STATE AND DYNAMICAL PROPERTIES OF ATOMIC OPTICAL BISTABILITY

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We dedicate this book to our parents

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Preface

Atomic optical bistability (AOB) has been a very active field of research in eighties because of its potential application in all-optical logic and switching devices. Bistability was first observed in a passive atomic medium of sodium vapor in 1974 and since then a wide range of activities started in this field of research, and many nonlinear materials including semiconductors were investigated for bistability. The main research was centered on optimizing the size of devices, switching times, operating powers, operating temperatures and other operating conditions. There have been a comprehensive book and some review articles for AOB in two-level systems, such as the excellent book by H. Gibbs: *Optical Bistability: Controlling light with light* (Academic Press, 1985) and a review article by L. A. Lugiato: *Theory of optical bistability in 'Progress in Optics'*, Vol. 21, p.71 (edited by E. Wolf, North Holland, Amsterdam, 1984). Also, the phenomenon of optical bistability has been discussed in several text books, such as '*Nonlinear Optics*' by R. W. Boyd (Elsevier, 3rd Edition, 2008).

In the decade of nineties a great deal of research activities have been seen in the area of multilevel atomic systems exhibiting the phenomenon of electromagnetically induced transparency (EIT). The multilevel atomic system has several advantages over the two-level system as absorption, dispersion, and nonlinear optical properties of one optical field coupled to one atomic transition can be greatly modified by another optical fields coupled to nearby atomic transitions due to the induced atomic coherences. By using such changes in linear and nonlinear optical properties around resonance, due to the EIT, it is easy to manipulate and control nonlinear optical processes in the multilevel atomic systems. Such controls are not available in the two-level atomic system, which have stimulated new research interests in the area of AOB using multilevel atomic systems inside the optical

cavity. Hence, one of the new research areas is the controllability of AOB in a three-level atomic system inside an optical cavity, emphasizing the enhanced nonlinear optical process due to induced atomic coherence in such intracavity EIT medium. All-optical switching using AOB and dynamical hysteresis in AOB were studied using the three-level atomic system. Investigations of controlled optical dynamic instability and chaos in the cavity output field with three-level atoms inside an optical cavity were carried out. Phenomenon of stochastic resonance in AOB and noise-induced transitions became easily accessible experiments because of the enhanced nonlinearity in the intracavity EIT medium. Some of those effects have not been observed previously in two-level AOB systems.

The book presents the descriptions of unique controllabilities available in the multilevel EIT systems for studying AOB and related effects, along with the underlying physics encompassing those phenomena. The book is aimed at both graduate level courses and beginning researchers in these areas of AOB and related effects. It can also serve as a reference book for many interesting aspects of nonlinear optical phenomena. We first introduce the background materials for two- and three-level atomic systems useful in understanding optical bistability, multistabilities, dynamic instability, chaos, stochastic resonance, and all-optical as well as noise-induced switching. The book is written at a level comprehensible to readers with the background of a beginning graduate student in the disciplines related to physics and electrical engineering having some good understanding in mathematics, and electricity-magnetism. The other purpose of the book is to develop in detail the central results of optical bistability and associated phenomena with multilevel atomic media inside optical cavity. Through studying this book, the reader should develop a working understanding of fundamental tools and results of this exciting field, and be able to carry out independent research in areas related to AOB and other nonlinear optical processes in multilevel systems.

The basic structure of the book is as follows. Chapter 1 gives an introduction and fundamental concepts of interaction of electromagnetic field with two- and three-level atomic systems, electrical susceptibilities, nonlinearities of these systems, highlighting some open issues along the way. A broad overview for the main concepts and results of multilevel EIT systems, including controllable linear absorption and dispersion properties in three-level atomic systems are presented. The in-depth fundamental notions of AOB along with the historical development for the simple case of two-level atoms are reviewed in Chapter 2. In Chapter 3 the discussion on cavity line-

narrowing effects and cavity ring down spectroscopy with three-level EIT systems are given. This Chapter also provides formulation of steady-state AOB with three-level atoms inside an optical cavity, which is followed by descriptions of recent experiments showing controls of shape and rotation direction of the hysteresis cycles by the coupling beam frequency detuning and other experimental parameters. The background material and origin of optical multistability in two- and three-level atoms in terms of the general principle are discussed in Chapter 4. The discussion is further enhanced by incorporating some successful experimental demonstrations of optical multistability in the laboratory.

Chapter 5 describes theoretical and experimental investigations of controlled optical dynamic instability and chaos in the cavity output field with three-level atoms inside an optical ring cavity. The route to chaos via period doubling and its characterization with the help of diagnostic recipes of Fourier transform and Lyapunov exponent calculations are discussed.

In Chapter 6, experiments describing deterministic switching are discussed. The basics of all-optical switching phenomena and their controls using Kerr nonlinearity are described, which were demonstrated in the basic three-level AOB system inside an optical cavity. In such experiments the cavity (probe) output field intensity could be controlled by the coupling field intensity or frequency detuning. The importance of such all-optical switching in optical computation is also highlighted.

The dynamical hysteresis, stochastic resonance and noise-induced transitions in the three-level AOB system are explained in Chapter 7. The formulations of these phenomena, both qualitatively and with simplified mathematical models, are presented in this Chapter. Then, a few novel experiments done in laboratory are discussed.

Some concluding remarks and outlooks are given in Chapter 8 which summarizes this book with emphasis on the unified central theme: controllable cavity output (both steady-state and dynamical behaviors) with a modified linear and nonlinear intracavity medium of an ensemble of three-level EIT atoms.

We would like to thank many colleagues who have worked with us over the years on the topics presented in this book, especially H. Wang, D. J. Goorskey, W. Yang, and A. Brown. We also thank our families for their supports and understanding.

Amitabh Joshi
Min Xiao

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