Dynamics of coherent population trapping states in dense systems

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We investigate the characteristics of the coherent population trapping (CPT) states in a dense medium. We incorporate the local-field effects into the density-matrix equations and numerically integrate the resulting nonlinear equations. We find that the CPT state is essentially unaffected by the local-field effects for all ranges of field strengths; however, states close to the CPT state are sensitive to them. We demonstrate a dispersive behavior near the CPT state in a dense medium besides important asymmetries and shifts of the Autler-Townes peaks in absorption spectra. We also study the effect of local fields on the dynamics before CPT occurs and show that the evolution to the CPT state is delayed due to the local fields. We extend our calculation to analyze lasing without inversion in a dense medium of \(\Lambda\) systems.

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I. INTRODUCTION

Alzetta et al. [1] first observed nonabsorption resonances in the fluorescence from sodium vapor illuminated by a multimode laser field. It was found that a decrease in fluorescence intensity occurred when some hyperfine transitions of the ground state matched the frequency difference of the two laser modes. Other experimental studies by Gray, Whitley, and Stroud and Murnick et al. [2] followed by a theoretical study by Orriols [3] indicated that the above phenomenon now termed coherent population trapping (CPT) was a result of the nonlinear effects of coherence and interference due to simultaneous excitation pathways. It was established that a three-level system with two closely spaced ground levels optically coupled to a common excited level by two coherent fields gives rise to trapping of population in a coherent superposition of the ground levels which is immune to further excitation. The nonevolving, nonabsorbing coherent superposition state is called the CPT state and this occurs whenever the frequency separation between the fields is equal to the separation between the ground levels (which is the two-photon resonance condition).

Over the years the conditions leading to CPT in \(N\)-level systems, especially three-level systems, have been studied [4] and the various factors influencing CPT, like strength of the laser fields, spontaneous decay rates, etc., have been established [5]. CPT has also been dealt with in the quantum regime and some novel properties discovered [6]. In a recent work [7] the authors have shown that CPT in the \(\Lambda\) system persists even at low light levels. A dynamical study demonstrates that as the field strength is reduced it takes longer and longer to reach steady state.

Originally CPT was studied due to the interest in maximizing the upper-state population for efficient laser isotope separation or selective excitation processes. With the proposal of lasing without inversion systems, however, CPT came to be recognized as a potential means of realizing a novel kind of lasing [8]. In recent years CPT has been utilized to demonstrate lasing without inversion [9] and efficient transfer of population [10].

However, all the previous studies on CPT have been done in dilute media. An important factor which has not been taken into account is the effect of the neighboring atoms (called the dipole-dipole effect) on an atom, in a dense medium. The dipole-dipole effects influence the optical response of the atomic medium. The effective field acting on an atom is no longer just the macroscopic field but the local field which is due both to external sources and to all other atomic dipoles of the sample. It is related to the macroscopic field \(\vec{E}\) and the polarization \(\vec{P}\) via the Lorentz-Lorenz relation [11]

\[
\vec{E}_l = \vec{E} + \frac{4\pi}{3}\vec{P}.
\]

This correction to the macroscopic external fields leads to a nonlinear relationship between the macroscopic susceptibility and the microscopic polarizability. The correction to the response was derived by Bedeaux and Bloembergen [12]. Hartmann and co-workers predicted [13] a Lorentz redshift in the response of a two-level medium in the presence of local-field corrections (LFC’s). In a recent experiment Maki et al. [14] measured the optical response of a dense potassium vapor under conditions where local-field effects are important. Their results confirmed the predictions of the linear and nonlinear response theories and also demonstrated that the densities required for the local-field effects to be important are not large. A density around \(10^{17}\) cm\(^{-3}\) of sodium atoms is sufficient to obtain a shift of about 1 GHz of the sodium \(D\) line. Also LFC’s have been shown to lead to an

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