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Model of the atom laser with Raman outcoupling

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In the present paper, the authors start from the interaction of a system of two-level atoms with an electromagnetic field to drive the interaction Hamiltonian between these two-level atoms. Second, introduce the equations of motion which describing the dynamics of atom laser depending on the interaction Hamiltonian, this interaction Hamiltonian will be used to describe the outcoupling process in a Raman atom laser. Also, the authors model the dynamics of an atom laser produced by outcoupling three-level atoms from a Bose-Einstein condensate (BEC) via a Raman transition and investigate the transfer of quantum statistics from one of the optical modes to the atomic field. Finally, the authors mathematical treatment leads to the same as equations appears in literature which allowed obtaining the dynamics for any atom laser systems. © *2011 Laser Institute of America.*

Key words: dynamic of atom laser, Raman outcoupling, interaction Hamiltonian

I. INTRODUCTION

The recent development of the atom laser[1–7] has opened up the possibility of a revolution in atom optics just as the optical laser revolutionized photon optics. The useful characteristics of optical lasers such as mode selectivity, temporal coherence, and high spectral density occur for the atom laser. The last two properties in particular will be vastly improved by the realization of a truly continuous atom laser.[6] For an optical laser to have minimum linewidth and hence maximum spectral flux, it must be continuously pumped and come to steady state in a single-mode operation.[7] The generation of squeezed light is a mature technique in quantum optics, and it allows the observation of quantum phenomena such as antibunching. Squeezing in optics leads to entanglement, as the outputs of a squeezed state on a beam splitter are entangled, in contrast to the outputs from a coherent state on a beam splitter, which are uncorrelated.[8] The manipulation and control of the quantum state of a matter wave source will allow quantum field effects to be tested in atom optics. The generation of a squeezed atom laser will allow not only for the generation of entanglement but also for fundamental tests of quantum mechanics and nonlocality with massive particles, as well as increased sensitivity in atom interferometers. Squeezing is arguably more important in atom interferometers compared to optical ones, as the flux cannot be increased arbitrarily.[9] The generation of nonclassical light is well-established experimentally.[10] This suggests that a nonclassical atom laser output could be generated by transferring the quantum state of an optical mode to an atomic beam. Moore *et al.*[11] showed that a quantized probe field could be partially transferred to momentum "side modes" of a condensate consisting of three-level atoms in the presence of a strong pump field. Jing *et al.* performed a single mode analysis of the atom laser outcoupling process for a two-level atom interacting with a quantized optical field and showed that the squeezing in the optical field would oscillate between the optical field and the atomic field at the Rabi frequency.[12] As this was a single-mode analysis, the interaction with the atoms as they left the outcoupling region was not taken into account. Fleischhauer *et al.*[13] showed that Raman adiabatic transfer can be used to transfer the quantum statistics of a propagating optical field to a continuously propagating beam of atoms by creating a polariton with a spatially dependent mixing angle, such that the output contained the state of the probe beam.

An atom laser is produced by forming a Bose-Einstein condensate in a trapping potential, which can be formed from either exploiting the ac Stark shift, in the form of an optical dipole trap, or exploiting the Zeeman shift in the form of a magnetic potential. The atom laser beam is then produced by coupling these condensed atoms to free space. This can be achieved by allowing atoms to tunnel out of the trapping potential, or in the case of a magnetic trap, by applying some form of state-changing outcoupling process, which converts the internal state of the atom from one that is sensitive to the magnetic field, and hence experiences the trapping potential, to one that is magnetic field-insensitive, and hence is free to fall under gravity. State-changing outcoupling employs transitions between metastable ground states so that there is no spontaneous emission, usually Zeeman levels, or occasionally hyperfine levels. The coupling process between two ground states can be achieved by either a radio-frequency transition or by a two-photon optical Raman transition, which couples the two ground states via two optical fields detuned from an excited state. In this section the tools required to describe a system of atoms interacting with an

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