Semiclassical treatment and full quantum picture of resonance fluorescence from a modulated two-level system

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I will discuss the resonance fluorescence for several interesting physical systems and the resulting quantum interference effects. I will describe each scenario in both a semiclassical treatment where optical Bloch equations, quantum regression theorem, Floquet theorem, and Floquet-Liouville supermatrix formalism are applied, and a full quantum picture where the atom and photonic/phononic modes are all treated quantum mechanically. I will start with a detailed review of the textbook resonance fluorescence from a simple two-level system driven by a coherence laser field. Then I will reproduce the theories of resonance fluorescence from a two-level system driven bichromatically, where a quantum interference effect was predicted, and discuss the recent experimental demonstrations. Finally, I will explicitly show our work on resonance fluorescence and quantum interference from a modulated two-level system driven by a monochromatic laser field, which is an interesting atom-photon-phonon system in the quantum mechanical picture.

Contents

1 Introduction

Resonance fluorescence is one of the most interesting and important topics in quantum optics. The spectral features (including the frequency components, the intensity and linewidth of each spectral peak) of the resonance fluorescence of a simple two level system is a textbook example and has been demonstrated experimentally in a variety of systems [**?**, **?**,] i.e. the well-known Mollow triplet. Theoretically, Mollow triplet can be calculated via optical Bloch equations and quantum regression theorem, considering a semiclassical model where the atom has two quantum mechanical discrete energy levels while the laser is treated classically. Alternatively, the dressed-state picture, which is fully quantum mechanical and treats both the atom and the light field quantum mechanically, can be imagined to explain several characteristic spectral features.

Resonance fluorescence in the cases more complicated than a simple static two-level system driven by a simple monochromatic laser field has also been explored. During year 1993-1999, Z. Ficek and H.S. Freedhoff theoretically investigated the resonance fluorescence from a two-level system driven by a bichromatic field with one strong and one weak component [**?**, **?**, 1993,1996] and discussed the resulting quantum interference effect which causes the elimination of the central spectral peak [**?**, 1999] The semiclassical calculation of the spectrum can be performed using, again, the optical Bloch equations. However, in the monochromatic situation, we can work in the rotating frame since only one laser frequency is involved, whereas this does not work when we add one more light field. Therefore, the Hamiltonian we are considering here will have explicit time dependence and cannot be simply dealt with. The good news is that the Hamiltonian is periodically dependent on time, which is typically considered quasi-time-independent and Floquet theory can be then applied. A full quantum picture for the same system was then proposed to intuitively explain the resonance fluorescence spectrum, which is called the doubly-dressed picture since the atom in this case is dressed by two laser fields. Z. Ficek, together with T. Rudolph, later realized that a quantum interference effect can arise in this system when the two laser frequencies are carefully chosen, which can be very nicely explained in the doubly-dressed picture. This quantum interference effect has been experimentally demonstrated in year 2015 by J.-W. Pan's group and further explored with high-resolution spectroscopy in 2021 by Kai Mueller's group in self-assembled InAs/GaAs quantum dots. Similar quantum interference effect was also investigated theoretically for a four level system driven by a single laser field.

The system we are interested in is a two-level system whose energy level is modulated. We are interested in the resonance fluorescence spectral features when it is driven by a coherent laser field. The specific physical system we are considering is a self-assembled InAs/GaAs quantum dot modulated by a surface acoustic wave, benefiting from the fact that GaAs is a piezoelectric material. An acoustic cavity is fabricated to enhance a specific acoustic mode and the atom-phonon coupling. This device was originally used for the microwave-to-optical photon transduction project in NIST Quantum Nanophotonics group. Since this kind of quantum dot system has very nice quantum optical properties, it is perfect for our purpose as well. The initial motivation is that besides the Mollow triplet, the spontaneous emission spectrum from a modulated two-level system will have many orders of phonon sidebands, whose separation is typically a few GHz, depending on the phonon frequency (i.e. the acoustic wave frequency). The sideband position in Mollow triplet, on the other hand, is roughly the Rabi frequency, which can be also in the order of a few GHz. If we have both modulation and laser driving with the microwave and Rabi frequencies equal, the overlapping sidebands may result in some quantum interference effect. Unfortunately, this elimination of sidebands will not occur. Instead, the central spectral peak can be greatly suppressed due to quantum interference between different transition channels. This can be both analytically calculated using optical Bloch equations together with Floquet theorem, which is called the *Floquet-Liouville supermatrix formalism*, and physically pictured by a similar doubly-dressed picture where the atom, photon, and phonon modes are all treated fully quantum mechanically.

I will analytically calculate and discuss all the physics mentioned above, and foresee the experimental implementation of our theory in this note with a modulated quantum dot device.

2 Resonance fluorescence and Mollow triplet

2.1 Optical Bloch equation

2.2 Quantum regression theorem

2.3 Mollow triplet

2.4 Dress-state picture

3 Resonance fluorescence from a bichromatically driven two-level system and quantum interference

3.1 Many-mode Floquet theory

3.2 Floquet-Liouville supermatrix formalism

3.3 Doubly-dressed picture and quantum interference

3.4 Experimental demonstrations with spectroscopy

4 Resonance fluorescence from a modulated two-level system and quantum interference

4.1 Semiclassicaly treatment with Floquet-Liouville supermatrix formalism

4.2 Full quantum picture of dressed states and quantum interference

4.3 Experimental demonstration

References