URSI GASS 2021, Rome, Italy, 28 August - 4 September 2021

Harmonic Balance Based Analysis of Quantum Dot Systems

C. Moorman *(1), E. Lu (2) and C. Piermarocchi (2), and B. Shanker (1),(2)
(1) Department of Electrical and Computer Engineering
(2) Department of Physics and Astronomy
Michigan State University, Michigan, USA

Over the past decade there has been increasing interest in modeling at the boundaries of classical and quantum mechanics. This is not just an academic exercise, but one with a tremendous potential to engineer novel systems that use quantum mechanics for practical applications. One such application is the development of quantum memories (a crucial component for quantum information networks) [4]. These devices rely on orderly or random arrangements of atoms, impurities or quantum dots. These systems involve a large number of coupled elements, and a full quantum mechanical simulation of realistic systems is untenable. A viable approach is to analyze such systems using a semi-classical approach. This approach provides sufficient insight into the physics while making considerable gains in computational time and allowing for an engineering-based approach to design. Typically, semi-classical approaches to describe ensembles of atoms/impurities/dots coupled to radiation are based on Maxwell-Bloch equations [3]; here classical analysis is used to compute radiated fields and quantum is used to describe the internal dynamics of the quantum elements.

Given the burgeoning interest, our group has focused on solid state quantum memories based on semiconductor quantum dots, and has driven the adaptation of state-of-the-art computation electromagnetics tools to their analysis; these include time domain integral [2] as well time domain adaptive integral methods [1]. Both these techniques still rely on a transient analysis and coupling. They are robust in their ability to evaluate nonlinearities that arise from pairwise dot coupling. But the key stumbling block to the analysis is the long time analysis. The question that we seek to ask in this paper is whether there are other features of these systems that can be exploited for analysis. The fundamental feature of a quantum-dot system is that it is inherently narrowband. If so, can we exploit this feature to develop a solution method?

Harmonic balance analysis is a hybrid technique which has found widespread application in design and analysis of RF-circuits [5]. This technique relies on a Fourier representation to match transient responses and determine unknown coefficients. This technique has long served as a complement to time-domain methods for evaluating nonlinear circuits, and has the same potential in the realm of quantum dots systems. With an adequate initial guess for a Newton solver, the frequency spectrum can be shaped numerically. In this paper, we examine the frequency spectrum of quantum dot systems with various dot configurations, excitations, and simulation lengths using data from time-domain codes. We will present a development of a multi-tone harmonic balance technique [6], and we will demonstrate its application to increasingly large systems of quantum dots within a wide range of temporal duration.

References

[1] C. Glosser, E. Lu, T.J. Bertus, C. Piermarocchi, and B. Shanker. Acceleration techniques for semiclassical maxwell¿bloch systems: An application to discrete quantum dot ensembles. *Computer Physics Communications*, 258:107500, 2021.

[2] Connor Glosser, B Shanker, and Carlo Piermarocchi. Collective rabi dynamics of electromagnetically coupled quantum-dot ensembles. *Physical Review A*, 96(3):033816, 2017.

[3] Michel Gross and Serge Haroche. Superradiance: An essay on the theory of collective spontaneous emission. *Physics reports*, 93(5):301–396, 1982.

[4] D. Higginbottom. *Atom-light couplers with one, two and ten billion atoms*. PhD thesis, Australian National University, 2018.

[5] S. A. Mass. *Nonlinear microwave and RF circuits*. Milton Keynes UK: Lightning Source UK. Ltd., 2011.

[6] A. Ushida and L. Chua. Frequency-domain analysis of nonlinear circuits driven by multi-tone signals. 31:766–779, 1984.