

Evolution of a low-frequency impulse in a medium of asymmetric atomic systems

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Abstract

Coherent, optically dressed media composed of two-level atomic systems without inversion symmetry make optically tunable sources of radiation in the GHz-THz domain. Here, full propagation dynamics of such low-frequency impulses is investigated to eventually formulate conditions for stable impulse buildup.

A two-level atomic system is one of the simplest examples one can investigate in the context of interactions with light. Nevertheless, there is still room for new or poorly examined phenomena. If a two-level atomic system characterized by inversion symmetry in space, such as an atom, is coupled to a classical electromagnetic field, it undergoes Rabi oscillations where the population flips between the ground and excited levels. In this contribution we investigate a scenario, where a system of broken inversion symmetry is used instead. In such case the dynamics is modified for the following reason: Eigenstates of an asymmetric system can be characterized with a permanent electric dipole moment originating from the polarization of charges, which plays a significant role of an additional source of dipole radiation. Its frequency corresponds to the Rabi frequency of population transfer between the eigenstates [1, 2], and therefore is optically tunable with the intensity of the driving field. If the driving field is strong, the frequency of the generated impulse might reach the terahertz regime.

For a realistic description of the process and access to the full propagation dynamics, it is essential to examine not only one individual two-level system, as in previous works [1, 2], but a coherent ensemble thereof. For this purpose we apply a semiclassical approach, to describe a medium of two-level asymmetric systems driven by a strong coherent beam of light $\mathbf{E}_{\text{drive}}(t)$, and being a source of dipole radiation at Rabi frequency $\mathbf{E}_{\text{Rabi}}(\mathbf{r}, t)$. The interaction Hamiltonian describing the process reads

$$\hat{V} = -[\mathbf{E}_{\text{drive}}(t) + \mathbf{E}_{\text{Rabi}}(\mathbf{r}, t)] \cdot \hat{\mathbf{d}},$$

where $\hat{\mathbf{d}} = \sum_{i,j \in \{e,g\}} \mathbf{d}_{ij} |i\rangle \langle j|$ is the dipole moment operator of the asymmetric system, while e and g correspond to the excited and the ground state of the system. Its diagonal elements stand for the permanent dipole moments in the system's eigenstates. They are unique to asymmetric two-level systems and have typically been neglected.

In our semiclassical approach, optical Bloch equations are used to describe dynamics of the medium, in particular to evaluate its polarization $\mathbf{P} = N \text{Tr}(\rho \hat{\mathbf{d}})$. Here, N is the number of two-level systems per unit volume and ρ is their density matrix. The polarization is a source in the Maxwell's wave equation describing the propagation of the generated low-frequency pulse $\mathbf{E}_{\text{Rabi}}(\mathbf{r}, t)$, initially being zero and gradually building up and propagating in the medium.

Two approximations commonly applied in similar problems are the rotating wave approximation (RWA) removing fast oscillations from evolution equations, and the slowly varying envelope approximation (SVEA) valid if frequency of the pulse largely exceeds the inverse time-scale of the dynamics set by Rabi frequency. Here, the RWA must be adjusted to account for oscillating permanent dipole moments, essential for the impulse buildup. The SVEA is not applicable, since the frequency of the generated pulse precisely corresponds to the time-scale of dynamics of the investigated system.

In general, the impulse propagation equation coupled to Bloch equations for the medium cannot be solved analytically. Therefore, a numerical approach is applied [3]. We construct a solver to calculate dynamics of an impulse propagating along the medium driven by an electromagnetic field in the visible domain. The goal is to identify realistic parameter regimes for future experiments where a stable buildup of the low-frequency impulse occurs.

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- [2] P. Gładysz, *Asymetryczny układ dwupoziomowy w oddziaływaniu ze światłem*, bachelor thesis, Toruń (2017).
- [3] H. Loui, *1D-FDTD using MATLAB*, ECEN-6006 Num. Meth. in Photonics Proj. 1, 1–13 (2004).