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Population density gratings creation and control in resonant medium by half-cycle terahertz pulses

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Abstract. Electromagnetically induced gratings (EIG) are created by standing-wave laser field in resonant media. Such gratings can be also created by few-cycle electromagnetic pulses counter-propagating in the medium via coherent Rabi oscillations of atomic inversion. In this case, instantaneous cross-section of the pulses in the medium is not necessary for grating formation. In this paper, we revise our recent results in study of such grating formation and their control by few-cycle pulses coherently propagating in a resonant medium. We demonstrate the grating formation and their control in three-level medium excited by three subcycle THz pulses.

1. Introduction

Electromagnetically induced gratings (EIG) are resulted via interference pattern created by pair of monochromatic beams overlapping in the medium [1]. Such gratings are typically created in three-level atomic systems when two counter-propagating pump laser beams form standing-wave and the electromagnetically induced transparency (EIT) regime is realized [2]. EIG created in this way have attracted considerable interest in recent decades [3-8]. In particular, they have applications in all-optical communications, including optical switching [3], beam splitting [4], observation of Talbot effect [5], and topological photonics [6]. EIG are obtained in plenty of systems and the diffraction pattern of the probe beam diffracted on such EIG is actively investigated so far [7, 8].

Generation of ultra-short pulses with duration order of electromagnetic oscillation period in different spectral ranges became of great interest in optics [9]. Among them, considerable interest lies in the field of broadband terahertz (THz) pulse generation [10, 11]. The duration of such pulses is much shorter than medium polarization relaxation time T_2, so they can interacts with resonant medium coherently. Namely, few-cycle pulses via coherent Rabi flopping can change the atomic inversion very fast within the time scale of pulse duration. The train of long [12] as well as few-(single and subcycle) pulses can create population density grating in the medium via Rabi oscillations of atomic polarization and inversion [13-21]. In this case, pulses do not overlap in the medium.

The possibility of such gratings formation and their control was studied theoretically by us in the optical range using femto- and attosecond pulses [13-19]. However, creation of EIG in this case requires strong amplitude of the driving pulses (~10^6 V/cm). In [20] grating dynamics created by subcycle and unipolar THz pulses was studied. It was also shown that using a medium having resonances in the THz range and high values of transition dipole moments allows to use THz pumping pulses with field strengths much lower (~10^3 V/cm) than in the optical range. Furthermore, using half-cycle quasi-unipolar THz pulses allows more efficient grating creation and control with respect to long multi-cycle ones [20]. We remark that there is a considerable interest to the problems related to unipolar subcycle pulse generation and their interaction with a resonant medium so far [22]. In particular, such gratings created by unipolar pulse can be used in holography with ultra-high time resolution and mutual coherence between reference beam and a beam scattered by an object [23].

In the first papers, grating dynamics was studied in two- [13-16] and in three-level medium [18]. In [17, 19, 20] this possibility was generalized to multi-level media using approximate solution of time dependent Schrödinger equation in the perturbative regime when the driving field amplitude is small. Numerical simulations performed for 3-level medium were carried out when the medium was excited by a pair of unipolar pulses [18, 20].

In this paper, we study theoretically grating dynamics in a three-level medium having resonance in the THz range and excited by three subcyle THz pulses.

2. The model and results of numerical simulations

Let the resonant medium be spaced along the z-axis and having low atomic concentration excited by a pair of counter-propagating pulses with temporal profile:

$$\mathrm{E}_{exc}(\mathrm{t}) = \mathrm{E}_0 \mathrm{e}^{\frac{-\mathrm{t}^2}{\tau^2}} \cos(\Omega \mathrm{t} + \phi) + \mathrm{E}_0 \mathrm{e}^{\frac{-(t-\Delta)^2}{\tau^2}} \cos(\Omega[\mathrm{t} - \Delta] + \phi). \quad (1)$$

Here E_0 is the pulse amplitude, τ the pulse duration, Ω the central frequency, and ϕ the carrier envelope phase (CEP). $\Delta \sim z/c$ is the delay between pulses depending on the space coordinate. Since particles concentration is assumed to be low, pulse shaping via propagation in the medium can be neglected. In such situation, the population changes in space can be studied via single-particle response dependence versus the delay between two pulses $\Delta \sim z/c$ [13-20].

The population of the n-th quantum state after the pulses calculating in the 1st order pertubation theory is given by [20]

$$w_n = \frac{d_{1n}^2}{\hbar^2} E_0^2 \tau^2 \exp\left[-\frac{(\omega_{1n}^2 + \Omega^2)}{2}\right] [\cosh(\omega_{1n}\Omega\tau^2) + \cos 2\phi][1 + \cos(\omega_{1n}\Delta)]. \quad (2)$$

Here d_{1n} and ω_{1n} are the transition dipole moment and transition frequency, respectively. This formula shows that harmonic EIG of inversion can be created in a resonnant medium. Using a train of few-cycle pulses, we can control the grating properties. Let the 3rd identical pulse be launched into the medium behind the 2nd pulse in the same direction. The total field has the form

$$\mathrm{E}_{exc}(\mathrm{t}) = \mathrm{E}_0 \mathrm{e}^{\frac{-\mathrm{t}^2}{\tau^2}} \cos(\Omega \mathrm{t} + \phi) + \mathrm{E}_0 \mathrm{e}^{\frac{-(t-\Delta)^2}{\tau^2}} \cos(\Omega[\mathrm{t} - \Delta] + \phi) + \mathrm{E}_0 \mathrm{e}^{\frac{-(t-\Delta-\Delta_{23})^2}{\tau^2}} \cos(\Omega[\mathrm{t} - \Delta - \Delta_{23}] + \phi). \quad (3)$$

Here Δ_{23} is the delay between the 2nd and the 3rd pulse. In this case, an analytical expression for the population of the n-th states after pulses is more complex than Eq. (2) and can be also obtained, see [20]. For a clearer illustration of the dynamics of the lattices in this case we use numerical simulations. Let us consider a three-level medium having equidistant harmonic-oscillator type level structure with resonant transition frequency $\omega_{21} = \omega_0 = 2\pi \times 1$ THz. Such situation can describe vibrational states in molecules having resonances in the THz range. The medium is excited by 3 THz pulses in the form Eq. (3). The interaction of the three-level medium with a pumping field is described by the system of density matrix elements having the form:

$$\frac{\partial}{\partial t}\rho_{21} = -\frac{\rho_{21}}{T_{21}} - i\omega_{21}\rho_{21} - i\frac{d_{12}}{\hbar}E(\rho_{22} - \rho_{11}) - i\frac{d_{13}}{\hbar}E\rho_{23} + i\frac{d_{23}}{\hbar}E\rho_{31}, \quad (4)$$

$$\frac{\partial}{\partial t}\rho_{32} = -\frac{\rho_{32}}{T_{32}} - i\omega_{32}\rho_{32} - i\frac{d_{23}}{\hbar}E(\rho_{33} - \rho_{22}) - i\frac{d_{12}}{\hbar}E\rho_{31} + i\frac{d_{13}}{\hbar}E\rho_{21}, \quad (5)$$

$$\frac{\partial}{\partial t}\rho_{31} = -\frac{\rho_{31}}{T_{31}} - i\omega_{31}\rho_{31} - i\frac{d_{13}}{\hbar}E(\rho_{33} - \rho_{11}) - i\frac{d_{12}}{\hbar}E\rho_{32} + i\frac{d_{23}}{\hbar}E\rho_{21}, \quad (6)$$

$$\frac{\partial}{\partial t}\rho_{11} = \frac{\rho_{22}}{T_{22}} + \frac{\rho_{33}}{T_{33}} + i\frac{d_{12}}{\hbar}E(\rho_{21} - \rho_{21}^*) - i\frac{d_{13}}{\hbar}E(\rho_{13} - \rho_{13}^*), \quad (7)$$

$$\frac{\partial}{\partial t}\rho_{22} = -\frac{\rho_{22}}{T_{22}} - i\frac{d_{12}}{\hbar}E(\rho_{21} - \rho_{21}^*) - i\frac{d_{23}}{\hbar}E(\rho_{23} - \rho_{23}^*), \quad (8)$$

$$\frac{\partial}{\partial t}\rho_{33} = -\frac{\rho_{33}}{T_{33}} + i\frac{d_{13}}{\hbar}E(\rho_{13} - \rho_{13}^*) + i\frac{d_{23}}{\hbar}E(\rho_{23} - \rho_{23}^*). \quad (9)$$

Here ρ_{21}, ρ_{32}, ρ_{31} are nondiagonal elements of density matrix, ρ_{11}, ρ_{22}, ρ_{33}, are populations of the 1st , 2nd and 3rd level, respectively, d_{12}, d_{13}, d_{23} are the transition dipole moments, $\omega_{21} = \omega_0 = \omega_{32}$, $\omega_{31} = 2\omega_0$ are the transitions frequencies, T_{ik} are the relaxation times of the diagonal and nondiagonal elements.

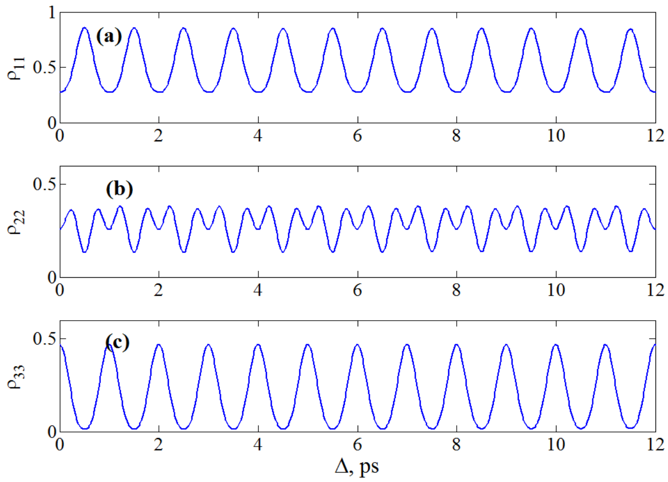

Figure 1. Populations of the 1st ρ_{11} (a), 2nd ρ_{22} (b) and 3rd ρ_{33} level as a function of delay between the 1st and 2nd pulsesΔ. The parameters of numerical simulations: $\Delta_{23} = 2$ ps was fixed, $E_0 = 15$ kV/cm, $\tau = 500$ fs, $\Omega = \omega_0 = 2\pi \times 1$ THz, $\phi = 0$, $d_{12} = 18.8$ Debye, $d_{23} = 26.7$ Debye, $d_{13} = 0$, $T_{22} = T_{33} = 1500$ ps, $T_{21} = T_{32} = T_{31} = 500$ ps.

The populations of the 1st ρ_{11}, 2nd ρ_{22} and 3rd ρ_{33} levels as a function of the delay between the 1st and 2nd pulses Δ are plotted in Fig.1. It is seen that ρ_{11} and ρ_{33} have harmonic shapes, at the same time ρ_{22} has a complex peak structure. Fig.1 also illustrates the possibility of selective excitation of the level populations – at certain values of the delay population of some level is minimum and others are more populated. The possibility of selective excitation of quantum states by a pair of subcycle pulses was reported in [19, 21].

Corresponding population inversion gratings dynamics versus time and delay Δ is shown in Fig.2. It is seen that inversion grating $\rho_{11} - \rho_{22}$ has almost harmonic shape. Meanwhile, inversion $\rho_{11} - \rho_{33}$ has double peak structure, and inversion $\rho_{22} - \rho_{33}$ has more complex peak structure. A the same time for certain level of the delay population inversion is negative, see Fig.2b,c. The latter illustrates the possibility of population inversion creation in the medium, which can be used for lasing.

3. Conclusions

In this paper, we studied theoretically population density gratings dynamics in three-level resonant medium having harmonic-oscillator type level structures and resonance frequency in THz range excited by 3 subcycle THz pulses. The grating creation, control, selectivity of level excitation in single molecule, as well as possibility of population inversion formation was shown. In contrary to the common approach, in our case EIG are created by the train of few-cycle pulses nonoverlapping in the medium. The lifetime of EIG is limited by the medium relaxation times.

These EIG can find several applications in spectroscopy, holography, all optical communications, ultrafast laser beam deflectors, topological photonics and many other applications [1-8, 12-23].

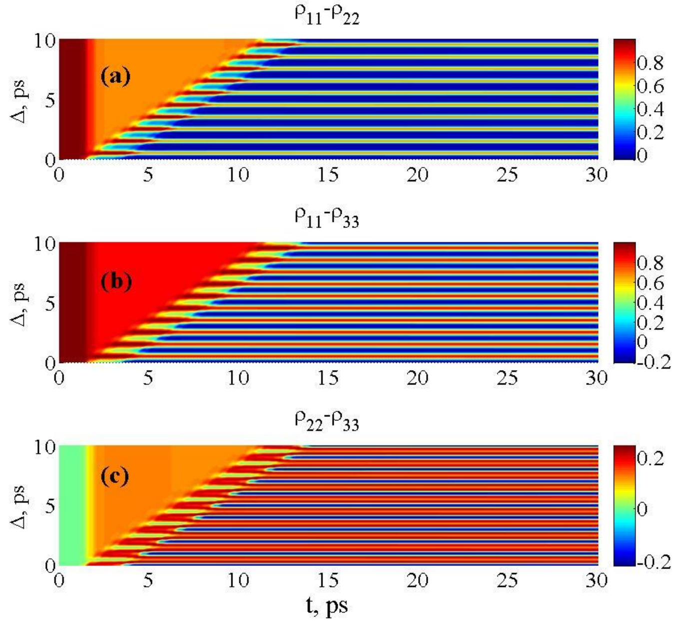

Figure 2. Population differences $\rho_{11} - \rho_{22}$ (a), $\rho_{11} - \rho_{33}$ (b) and $\rho_{22} - \rho_{33}$ versus delay Δ under the parameters of Fig.1

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