Islamic Azad University

Journal of Optoelectronical Nanostructures

Spring 2017 / Vol. 2, No. 2

IRANIAN SOLAR ENERGY SCIENTIFIC SOCIETY

Population change in the fine structure levels of cesium atoms using chirped laser

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(Received 27 Mar. 2017; Revised 18 Apr. 2017; Accepted 17 May. 2017; Published 15 Jun. 2017)

Abstract: Here, the population transfer between two specific levels of Cesium atom under the influence of chirped laser source has been numerically investigated. The main goal of this study is the engineering of the population transfer between the $6^2S_{1/2}$ and $6^2P_{1/2}$ levels of Cesium which is corresponding to its D_1 transition line using a chirped laser source. Constructing the system Hamiltonian, as well as the initial and boundary conditions, the time-dependent Schrödinger equations are numerically solved and the population versus time for different physical parameters has been investigated. The final population of each state is calculated and discussed for changing the parameters such as laser intensity, laser frequency and chirping parameter. The results show that using the chirped laser source with tuned parameters, we can arbitrarily control the population of levels.

Key words: atomic population transfer, chirped laser, cesium atom, two-level system.

1. INTRODUCTION

Population transfer in a two-level system driven by a controlled external source has been always of great interest in atomic experiments [1-14]. This is while development of tunable lasers provided an excellent method for researchers towards the realizing of this goal. Recently, short pulse lasers have become available over a frequency amplitude extending from infrared to ultraviolet [1, 20 and 21]. It is also shown that chirped pulse lasers, could be extensively used for the population transfer between atomic energy levels [1-14]. For example, some

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chirped laser applications in atomic system include: Ionization of the atoms [1], population transfer in two atoms molecules by analyzing the time-dependent wave packet on the electronic energy levels [2], Rydberg atoms transition to lower energy modes by chirped microwave pulses [3], controlled population transfer in multi-level molecules such as Li2 [4], and interaction of strongly chirped pulses with two-level atoms [5]. In the history of population transfer in 1932, Zener and Landau reported independently exact solution for a semi-classical model of one-dimensional for two states transition which is known as the Landau-Zener (LZ) model [7, 17]. LZ transition occurs when the two level system is influenced by an external time dependent sweeping source [16, 17]. LZ model is an important non-adiabatic population transfer model which has many applications in atomic physics. It should be noted that the LZ model and chirped laser population transfer are related to each other by rotating wave approximation (RWA). This model could be applied to atom interferometers, in which it is possible to measure the atomic interference via the Stark level splitting, [18]. Another case is Stückelberg oscillations in Rydberg atoms using an external radio frequency field [19].

In this work we have considered the population transfer between the energy levels of Cesium atom. Cesium which is an alkaline atom with one unpaired electron has many applications in atomic physics including its application in magnetic optical traps [22], and the changes in the population of its atomic levels is the basis of the atomic clocks and atomic magnetometers [23, 24]. The interaction of the Cs atom and the external magnetic field is mostly because of the magnetic moment of its unpaired electron, which is on the order of one Bohr magneton and corresponds to the electron spin. Furthermore, the absorption coefficient of the resonant polarized light strongly depends on the atomic spin state. Hence, the optical detection of the magnetic fields is due to the spin mediated light-matter interaction [24].

For the ground state of the cesium, orbital angular momentum is equal to $L = 0$ and the spin angular momentum S equals to $J = 1/2$. For the first excited state $L = 1$, $J = 1/2$ or $J = 3/2$. Thus there's two transition lines corresponding to $L = 0 \rightarrow L = 1$ transition. These two lines are called D_1 and D_2 line, respectively and typically would be shown as $[6^2S(1/2) \rightarrow 6^2P(1/2)]$ and $[6^2S(1/2) \rightarrow 6^2P(3/2)]$ [25]. It should be noted that although the structure of the levels of cesium atom is in the form multi-level but if the laser frequency is near the frequency of a particular transition, we can consider two-level model approximation for the study of the population transfer between them. Fig. 1 shows the fine structure atomic level corresponding to the D_1 transition line of the cesium atom.

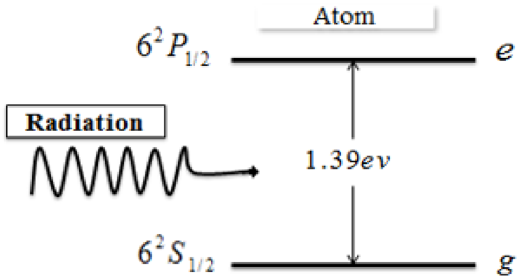

Fig. 1. Fine structure transition for D1 line at Cesium atoms.

2. THEORY

The Hamiltonian for a two-level system driven by laser source is as follows [26]:

$$H = \frac{1}{2}E_e\left(\mathrm{I}+\sigma_z\right)+\frac{1}{2}E_g\left(\mathrm{I}-\sigma_z\right)+\hbar\Omega\left(\sigma_+ + \sigma_-\right)\cos\omega_L t \qquad (1)$$

Where $\Omega = -(d.E)/\hbar$ is the Rabi frequency, E_g and E_e are the energy of the ground state and the excited state, I is the unit matrix, σ_z , σ_+ and σ_- are Pauli matrices and $\hbar$ is the Planck constant. In addition $\omega_L=\omega+\alpha t$ is the laser frequency, which ω is the carrier frequency and α is the chirping parameter.

The difference between the ground state and the excited energy levels corresponding to the D_1 transition of the cesium is equal to 1.39ev and so it's value in the natural frequency system is equal to 2.10� 10^{15} Hz Which is obtained by $\omega_0=(E_e - E_g)/\hbar$ [25, 26]. The first and second terms of the Hamiltonian are the energies of the excited and ground states and the last term determines the interaction energy between the laser field and the two-level system. It is worthy to note that the interaction Hamiltonian for small values of chirping parameter, could be transformed to the conventional LZ Hamiltonian using the RWA [26].

Using the Hamiltonian of Eq. (1) and the time-dependent Schrödinger equation, the following system of differential equation is obtained.

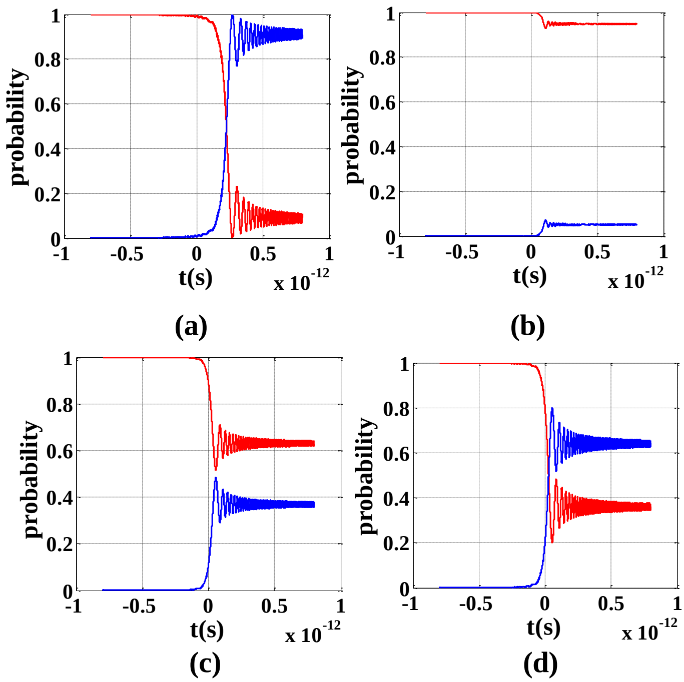

Fig. 2. Diagram of the population levels versus time for the two-level system. (a) ω=0.9 **,** α=0.5 , Ω =0.4 (b) ω=0.9 , α=1.5 , Ω =0.1 (c) ω=1 , α=0.7 , Ω =0.2 (d) ω=1 , α=0.7 , Ω =0.3.

$$i\hbar\begin{pmatrix}\dot{\psi}_1\\ \dot{\psi}_2\end{pmatrix}=\begin{pmatrix}E_e & \hbar\Omega\cos\left[(\omega+\alpha t)t\right]\\ \hbar\Omega\cos\left[(\omega+\alpha t)t\right] & E_g\end{pmatrix}\begin{pmatrix}\psi_1\\ \psi_2\end{pmatrix} \tag{2}$$

We have numerically solved Eq. (2) using Runge–Kutta method in a given time interval, and the time dependent population of the levels are obtained for different values of the laser intensity, laser frequency and chirping parameter. Furthermore, the probability of the states for each of the levels are calculated and investigated. It should be noted that for the initial conditions, it is assumed that the system is prepared in the pure ground state at very old times.

Here, we are looking to investigate the effect of the laser source parameters on the final states of the system. For this purpose, we have introduced a parameter called Final Probability of Ground state (FPG) as:

$$FPG=\int_{0.9T}^{T}|\psi|^2\,dt \tag{3}$$

Which gives the average of the 10% of the final state.

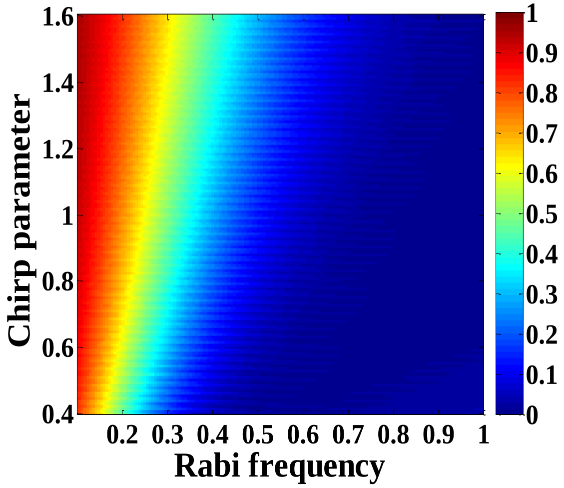

Fig. 3. FPG according to chirping parameter and Rabi frequency, for ω = 1.

3. RESULTS AND DISCUSSION

Time-dependent Schrödinger equations is numerically solved in the time interval of $-80\times10^{-14} \leq t_f \leq 80\times10^{-14}$. For the initial condition, it is assumed that in far past the system has been in ground state. Fig. 2 shows the effect of chirped laser on the probability of the population levels of the two-level system. For brevity in writing numerical values of the parameters, we have defined specific parameters unit. Because of their large valuse, the carrier frequency, the Rabi frequency and the chirping parameter are normalized. The carrier frequency is scaled by $\omega_0= 2.10\times 10^{15}$ Hz, Rabi frequency is scaled by 10^{14} Hz and the chirping parameter is scaled by 10^{27} Hz^2. In Fig. 2(a), the chirped parameter value is 0.5, Rabi frequency 0.9 and carrier frequency 0.4. This figure shows that in t = $-\infty$, the system is in ground state. However as time passes, and chirped laser irradiates, the major population transfers to the excited level and the transition take place. In Fig. 2(b), the chirping parameter value is equal to 1.5, carrier frequency is 0.9 and the Rabi frequency is 0.1. In this case, the population in both levels stay almost unchanged. In Fig. 2(c), $\alpha = 0.7$, $\omega = 1$ and $\Omega = 0.2$; it is evident that in this case, approximately 37% of the population of the ground state is transferred to the exited state by applying the laser irradiation. By increasing the carrier frequency to the value of $\omega = 1$ and reducing the chirping parameter, as well as increasing Rabi frequency, the transition probability is increased. Finally, in Fig. 2(d), by increasing Rabi frequency, the transition probability increase.

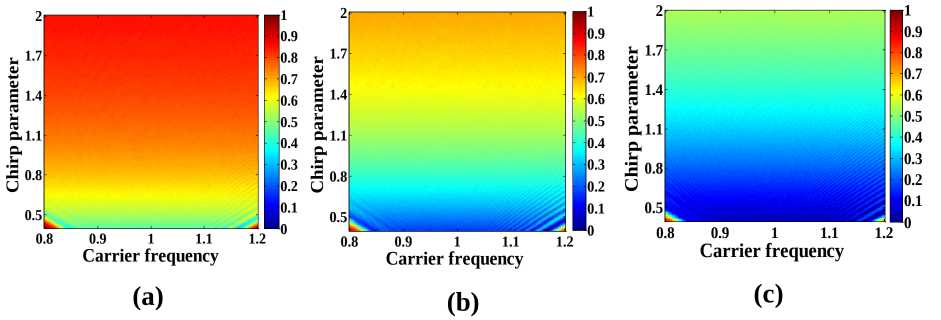

Fig. 4. FPG according to chirping parameter and carrier frequency for three values Rabi frequency, (a) $\Omega = 0.2$, (b) $\Omega = 0.3$, and (c) $\Omega = 0.4$.

In Fig. 3, FPG is plotted according to chirped parameter and Rabi frequency in $\omega = 1$. In this figure, the red areas show that the population remains in the ground state and blue areas show that the complete transition takes place. The areas between these two colors shows a final mixed state. In this figure, it can be seen that by increasing the Rabi frequency, transition probability increases and with increasing chirping parameter, transition probability decreases. Therefore, one can accurately control the amount of final population, by setting the appropriate laser parameters.

Fig. 4 shows the dependence of FPG to chirping parameter and carrier frequency for three different values of Rabi frequency. In Fig. 4(a), where $\Omega = 0.2$, it is evident that for large chirping parameters, transition probability is low and system is mainly remains in the ground state. By reducing the chirping parameter, mixed states appears and transition probability increases. It can also be seen that, in the considered interval, the carrier frequency does not have significant influence on the probability of transition. In Fig. 4(b), which is related to $\Omega = 0.3$, for low chirping parameter, transition probability is high and as this parameter increases, the transition reduce and mixed states appears. Fig. 4(c) shows that with further increasing of the Rabi frequency to $\Omega = 0.4$, the full transition areas increases, and the mixed states with a higher percentage of the excited state arises. Comparing three parts of Fig.4 for three values of Rabi frequency, it can be inferred that, with increasing the Rabi frequency, transition probability increases. For this purpose to view the impact of the resonant frequency, Fig. 5 shows the dependence of FPG to the Rabi frequency and carrier frequency, for the three smaller chirping parameter value. In Fig. 5(a), $\alpha = 0.05$, The resonance areas namely in the vicinity of $\omega = 1$, have complete transition but by increasing the difference between the carrier frequency and the natural frequency, the transition probability decreases quickly so that for $|\omega-1| >$

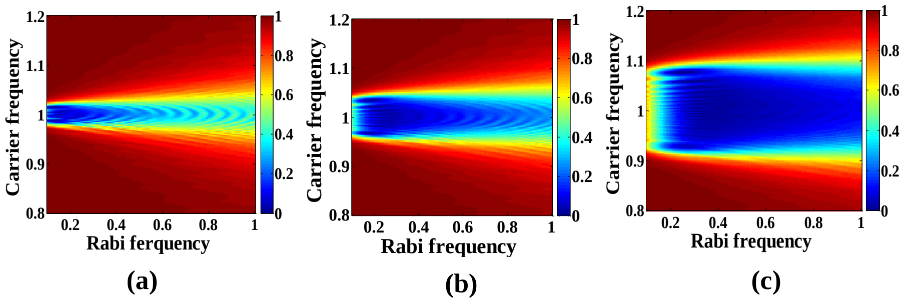

Fig.5. FPG based on the carrier frequency and the Rabi frequency for three chirping parameter value, (a) α = 0.05, (b) α = 0.1 and (c) α = 0.2.

0.02 there is no state transition. Fig. 5(b) shows the FPG for α =0.1. In this case, also for areas near resonance, in the range of 0.96 <ω <1.04, transition probability is close to one except for the very small (less than 0.1) Rabi frequencies. For carrier frequencies outside this range, there is initially small area consists of mixed state and for the carrier frequency farther from this area, states can be observed with zero FPG. In Fig. 5(c), chirping parameter is equal to α = 0.2. In this case the FPG behavior is similar to the previous case. Here, in the area near resonance 0.92 <ω <1.08 that is clearly greater than previous case, the complete transition occurs except for the very small (less than 0.2) Rabi frequencies that mixed state has been raised. This is while, increasing Rabi frequency in this range, reduces the transition zone respect to the case of Fig. 5(b). By comparing these three figures, it can be seen that, increasing the chirping parameter, increases the complete transition areas.

4. CONCLUSION

Here, we have investigated the effect of various parameters of chirped laser on the population of two-levels of the cesium atoms and it is shown that by adjusting the laser parameters, FPG can be arbitrary controlled. It is shown that at the large Rabi frequencies, the complete transition take places and at low Rabi frequencies, transition probability is reduced. In addition by increasing chirping parameter, the probability of transition would be decreased. For low chirping parameter, and carrier frequency close to the resonant frequency, even with very low laser intensity, population transfer easily occurs. In this case, it is shown that with increasing the laser intensity, the transition probability will be slightly decreased, however with increasing the chirping parameter, the system still would have complete transition.

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