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Effect of different polarized laser radiation in cooling and trapping of polariton

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Abstract

Light-matter interaction is gaining increasing interest at the frontiers of physics as it helps to understand many-body effects and explore their applications in optics and photonics. This research paper aims to investigate the effect of different polarized laser radiations in cooling and trapping process of polariton. Our strength lies in the analysis of the dynamic of polariton cooled and trapped with different types of laser-polarized modes in order to be able to formally recommend to the scientific community the best laser-polarized mode for realizing both theoretical and practical studies based on light-matter (polariton) interactions. From the complete Hamiltonian of the system, we derived the mechanical force and torque acting on the system and the transition probability of finding the system in the excited state using the semi-classical approach under rotating wave approximation (RWA). Our results demonstrate that laser cooling and trapping of polaritons is more appropriate using the plane polarized electric mode (PPEM) laser radiation than other types including the plane polarized electromagnetic mode (PEMM), the transverse polarized electric mode (TEM) and the transverse polarized magnetic mode (TMM), under low coupling strength constant and intense laser radiation. This finding is highly valuable for researchers and experts focused on optics and photonics as it provides new insights for advancing light–matter (polariton) interaction studies and potential quantum computing and teleportation applications.

Keywords: Polarized laser radiation; Cooling; Trapping; Polariton

1. Introduction

Polariton is by essence a quasi-particle which results from strong light-matter coupling in microcavities [1-3]. There are different types of polaritons including phonon-polariton, plasmon-polariton, magnon-polaritons, and exciton-polariton [4]. In the present study, our interest is directed to exciton polariton which results to strong light-matter coupling between a cavity photon and a semiconductor exciton in semiconductor microcavities [5]. Exciton-polariton will be call for simplicity polariton in the rest of the paper. The excitonic and photonic components of a polariton make it exceptional in condensed matter Physics [6, 7]. Indeed, since it discovery, it has been used as potential candidate in sensing [8, 9], imaging [10], subwavelength aperture transmission [11, 12], photodetectors [13, 14], nanoscale optical trapping [15] and optical nonlinearities [16, 17]. Besides, other important applications of polariton are mentioned by authors of Refs.[18-20]. Currently, many experiments are accomplished with the help of polariton [21]. In quantum

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communication and teleportation, polaritons are considered as quantum bits or qubits and are used for the encoding of information [22] with quantum computers [23].

Quantum computers are machines that implement a series of quantum mechanical operations known as unitary transformations on the qubits [24, 25]. These machines process the initial quantum states and evolve them into final ones that represent the results of a computational process [26]. The capabilities of quantum machines stem from their unique characteristics [27]. Unfortunately, their development remains challenging [21] to date because of the inherent conflict between DiVincenzo criteria [28] which demand a strong coupling to control and measure qubits and the need for a strong isolation from the uncontrolled environment to preserve coherence. Another factor explaining why quantum computers have not been realized to date is the distinguishable vacancies, adatoms, grain boundaries and substitutional impurities [29] of the materials used. Significant progress has been made in addressing these challenges [30, 31]. Recently, cooled and trapped polaritons entered the game [32, 33]. Their ability to address decoherence effects due to surrounding environment [33-38] comes not only from their enhanced sensitivity to external stimuli such as electric and magnetic fields [6], but also their status as major candidates in the design and implementation of quantum computers [39, 40] and simulators [41, 42]. Another factor that explains the ability of cooled and trapped polaritons in addressing decoherence effects due to surrounding environment in quantum computation and communication is that laser cooling and trapping of polariton can help to realize and stabilize the degree of entanglement between the atom and the field at a high level. For instance, the performance of these computational schemes depends on the type of laser-polarized mode used in cooling and trapping process.

Authors of Refs. [32, 33] investigated decoherence effects due to surrounding environment in a system of laser cooled and trapped polariton with [32] and without [33] the influence of magnetic field. For instance, the authors limited themselves to the case of plane polarized electromagnetic laser radiation. Meanwhile, different cases of polarized electromagnetic radiation can be considered, including and not limited to the PEMW, the TEM and the TMM, s/p-polarized and/or phase difference of E-field. These limitations observed in the previous studies [32, 33] together with the discussions above motivate the search for the effect of different polarized laser radiation on the dynamic of laser cooled and trapped polariton under the influence of a magnetic field, which we consider in this study as a trap.

The second part of this paper presents theoretical models and formalisms used to approach the problem. The third part deals with results obtained and their discussions. Finally, the paper ends up in the fourth section with a conclusion and future researches.

2. Theory

This section describes the theoretical formalism of our model. The general overview of the typical setup that we consider in the present study is depicted in FIG.1. For general formalism, we consider laser radiation applied onto an atomic entity [43-47], known as polariton in the present study. This quasiparticle will respond to the light field, and this response determines the amount of light that is transmitted and the one that is scattered. In order to quantify these aspects, we need to first characterize the different kinds of responses that we can expect from the quasiparticle. Upon doing so, we can define some important properties of the transmitted and scattered light. We have available a range of frameworks [48, 49] that we can use to describe events such as those portrayed in FIG.1. These can be broadly classified into the classical and semi-classical pictures. In the former picture, one models the atomic entity as a system of opposite charge coupled together by the classical harmonic oscillator [50]. Any oscillating light field, i.e. laser field, interacting with such elementary quasiparticle will result in the back and forth motion of the charge. Such a picture is completely classical because both the atom and the field are classical. For instance, in the latter picture, i.e. semi-classical picture, as the name suggests, one considers the atomic entities to be quantized and the light field to be a classical electromagnetic wave. Therefore, light-matter interaction can be modeled, as it's the case in the present study, in terms of a two-level system (TLS) being driven by an oscillating electromagnetic field [51].

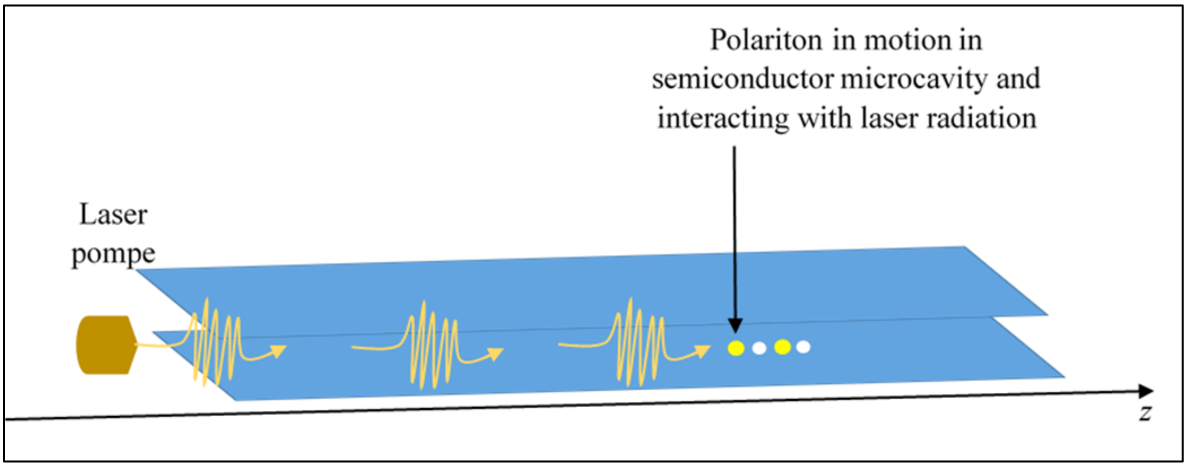

Figure 1 Typical picture of light-matter (polariton) interaction as considered in the present study. The laser radiation interacts with a polariton moving in the opposite direction than laser radiation. The direction of propagation of laser radiation is $z-$ direction

We consider a polaritonic entity surrounded by an electron cloud in semiconductor materials (FIG.2). In the absence of interaction with laser radiation, there is no net dipole moment (FIG.2a). In contrast, the cooling and trapping process with an external laser field will result in the oscillations of the electron cloud, thereby generating a net dipole moment (FIG.2b). To ease our calculations, we perform our analysis based on three main approximations. First, we focus our attention on the center of the system. Second, we assume that there is no interaction between the considered atomic entities with neighbors. Finally, we suppose that the batch do not have any influence on the dynamic of the system due to cooling and trapping phenomenon with laser light. From the approximations above, our analysis turns to the interaction of a laser radiation with a generic two-level dipole with possibilities to apply semi-classical approach under RWA. Of course, RWA has been proven a very good and incredibly useful tool to understand in the simplest way the concept of light-matter interactions [52]. Under this approach, physical parameters of interest include force and corresponding torque, transition probability and energy, and sometimes entropy. Here, we limit ourselves to the first three parameters. Since the focus point of the present study is to cool and trap the atomic entity with various types of radiation fields by reducing their displacement velocity, we found the force and corresponding torque as the appropriate parameters for controlling and manipulating the motion and orientation of atomic entities. Still, the atomic entity of our choice is the so far presumed polariton. Therefore, we consider the polariton as a dipole (TLS) made up of two elementary and oppositely charged particles $+q$ and $-q$ with masses m, separated by a distance $|d|$ and moving with velocity υ in an electromagnetic field E and B. The two elementary and opposite charged particles are placed at $d+\frac{r}{2}$ and $d-\frac{r}{2}$ respectively from the laser source (FIG.2c) where r is the center of mass coordinates.

The net force acting on a charge q at position r moving with the velocity υ when interacting with the laser field is entirely determined by the help of classical Lorentz equation (Eq.1),

$$F(r)=q[E(r)+\upsilon\times B(r)] \quad (1).$$

Based on Eq.1, the electromagnetic force acting on the dipole above takes the form of Eq.2

$$F=F(r+\frac{d}{2})+F(r-\frac{d}{2}) \cdot \quad (2).$$

When the field is uniform over the distance of $|d|$, we can approximate Eq.2 by expanding it in a power series of d, and neglecting the terms beyond the second order. Yield Eq.3 and Eq.4.

$$F\left(r+\frac{d}{2}\right)=F(r)+\frac{d}{2}F'(r)+\frac{d^2}{8}F''(r)=F(R)+\frac{d}{2}\nabla_r F(r)+\frac{d^2}{8}\Delta_r F(r) \quad (3),$$

$$F\left(r-\frac{d}{2}\right)=F(r)-\frac{d}{2}F'(r)+\frac{d^2}{8}F''(r)=F(r)-\frac{d}{2}\nabla_r F(r)+\frac{d^2}{8}\Delta_r F(r) \quad (4).$$

The substitution of Eq.3 and Eq.4 into Eq.2 and taking into account Eq.1 conducts to Eq.5.

$$F = d\nabla_r qE + d\nabla_r \dot{r}\times B \quad (5).$$

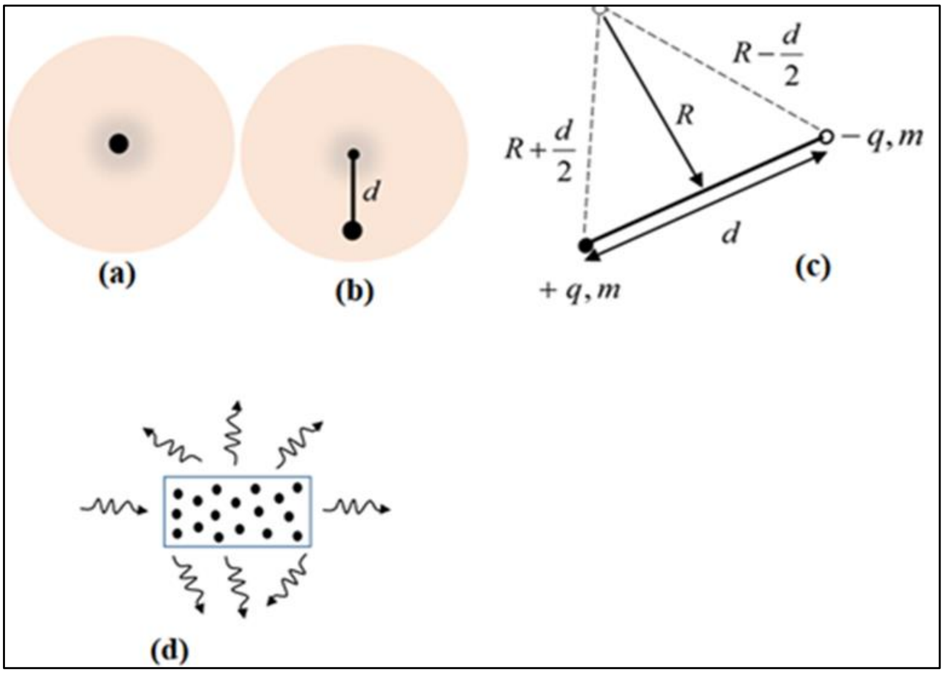

Figure 2 A possible semi-classical model of light-polariton interaction in terms of an induced dipole moment: (a) polaritonic entity out of interaction with laser radiation; (b) laser cooled and trapped polariton; (c) TLS approximation of an electric dipole moment setup considered in the present study (c); (d) Quantum considerations of light/matter(polariton) interaction in semiconductor microcavity

Using mathematical relations, including the derivative of a product of two functions f and g , and introducing the third derivative term, then Eq.5 takes the form of Eq.6 where the dots denote the differentiation with respect to time.

$$F = (\mu\cdot\nabla)E + \dot{\mu}\dot{r}^{-1}E + \dot{\mu}\times B + \dot{r}\times(\mu\cdot\nabla)B \quad (6).$$

If we consider the laser radiation as an electromagnetic field [53], then the final expression of the force acting on the system takes the form of Eq.7.

$$F = (\mu\cdot\nabla)E + \dot{\mu}\times B + \dot{r}\times(\mu\cdot\nabla)B = F_I + F_L + F_{IM} \quad (7).$$

In Eq.7, $\mu = qd$ is the dipole moment, F_I the inhomogeneous field-force, F_L the Lorentz force and F_{IM} the inhomogeneous field-force on the moving dipole moment which perceives the magnetic field in the reference frame as the electric field due to Lorentz transformation. In addition to exerting a force, an electromagnetic field can also transfer angular momentum resulting in a mechanical torque on a structure that is exposed to the field. If T is the mechanical torque acting on the charges in the electric dipole moment, then from the semi-classical approach yields,

$$T = \frac{d}{2}\times\left[F\left(r+\frac{d}{2}\right)-F\left(r-\frac{d}{2}\right)\right]. \quad (8).$$

Based on Eq.3 and Eq.4 and given that for the plane electromagnetic wave $\nabla \cdot E = 0$ and $\nabla \cdot B = 0$ in one hand and $d\nabla_r q(E + \upsilon \times B) = (\mu \cdot \nabla)E + \dot{\mu} \times B + \dot{r} \times (\mu \cdot \nabla)B$ in the other hand, yields Eq.9 and the net mechanical torque acting on the dipole interacting with laser radiation takes the form of Eq.10 with various parameters well defined above.

$$F\left(r + \frac{d}{2}\right) - F\left(r - \frac{d}{2}\right) = 2qE + 2q\upsilon \times B + \dot{\mu} \times \left(\frac{d}{4}\nabla\right)B \quad (9),$$

$$T = \mu \times E + \mu \times (\dot{r} \times B) + \frac{d}{2}\left[\dot{\mu} \times \left(\frac{d}{4}\nabla\right)B\right] \quad (10).$$

The application of Eq.10 to the interaction between laser radiation with an angular frequency ω_l and quasiparticle entity requires that $\lambda \succ\succ\succ |d|$. Moreover, we assume that $|E| = c|B|$. In order to perform our calculation with simplicity, another approximation have to be considered and these approximations are presented in details in Ref. [32].

The introduction of the approximations above conducts to the net mechanical force and torque acting on the system and are defined by Eq.11 and Eq.12 respectively.

$$F = (\mu \cdot \nabla)E + \dot{\mu} \times B = F_I + F_L \quad (11),$$

And,

$$T = \mu \times E \quad (12).$$

Determining the force and torque in Eq.11 and Eq.12, enable us to understand the time evolution of the electric dipole moment induced by the interaction between the polariton and the laser light. We face the issue of finding the correct Hamiltonian which describes the dynamic of laser cooled and trapped polariton. Within our formalism, we consider the simplest situation in which only one atomic transition mode of the polariton is considered, i.e. the excited state. We follow the theory used in Ref. [32] since the present research work is the continuity of that initiated in Ref. [32]. We consider our same electromagnetic laser radiation E and B, consisting of the electric field described by Eq.13 below and propagating toward the z-direction.

$$E = E_0 \cos(\Omega t - kz) \quad (13).$$

At unit $\hbar$, the full quantum Hamiltonian of the system is expressed by Eq.14 where H_0 is the polariton's Hamiltonian, $\omega a a^+ \otimes l_2$ the photon's Hamiltonian, $g(\sigma_+ a + \sigma_- a^+)$ the interaction polariton-laser Hamiltonian and $\mu E_0 \cos \Omega t \otimes \sigma_1$ the time dependent laser light Hamiltonian. μ is the component of the dipole moment along the direction of the light, g represents the coupling strength constant between the atom and photon; a^+ and a are the photon creation and annihilation operators respectively for the photon oscillation frequency Ω, σ_+ and σ_- are the pseudo-spin for the photon. The Hamiltonian Eq.14 is known as the Jaynes-Cummings one and such a typical transformation is called the Jaynes-Cummings model [54].

$$H = H_0 + \omega a a^+ \otimes l_2 + g(\sigma_+ a + \sigma_- a^+) - \mu E_0 \cos \omega_l t \otimes \sigma_1 \quad (14).$$

In order to solve the time-dependent Schrodinger equation $i\hbar \frac{d\psi}{dt} = H\psi$ using the total Hamiltonian H, it's important that the quantum state of the system should be elements of vector space of Lie algebra in the Fock's space over C given by $F = vect\{|0\rangle, |1\rangle\}$. Considering the matrix representation of the operators a^+, a and N, and giving that the complete Hamiltonian of the system should be Hermitian, then Eq14 takes the form of Eq.15. , where $\Delta = \omega_2 - \omega_1$.

$$H = \begin{pmatrix} \frac{\omega_1 + \omega_2}{2} - \frac{\Delta}{2} + \omega N & ga - \frac{\omega_R}{2} e^{i\Omega t} \\ ga^+ - \frac{\omega_R}{2} e^{-i\Omega t} & \frac{\omega_1 + \omega_2}{2} + \frac{\Delta}{2} + \omega N \end{pmatrix} \quad (15).$$

Following theoretical analysis investigated in Ref. [32], exact solution of the Schrodinger equation using Hamiltonian of the type Eq.15 conducts to different probabilities transition amplitudes $a(t)$ and $b(t)$ of finding the cooled polariton in the ground (Eq.16) and excited (Eq.17) states respectively, where $\theta^2 = \varphi^2 + g^2 + \frac{\omega_R^2}{4}$, $\omega_R = \mu E_0$, $\varphi^2 = \frac{\delta^2}{4} + g^2$, $\delta = \Omega - (\Delta + \omega)$, $A = \Lambda - \Delta - 2\omega N$ and $\Lambda = \Omega - \omega$.

$$a(t) = e^{it\frac{A}{2}} \left\{ \cos(\theta t) - i \frac{\delta}{2\theta} \sin(\theta t) \right\} \quad (16),$$

$$b(t) = i \frac{\omega_R}{2\theta} e^{-it\frac{A}{2}} \sin(\theta t) \quad (17),$$

The probability of finding the polariton in the excited state is then giving in Eq.18,

$$|b(t)|^2 = \frac{\omega_R^2}{4\theta^2} \frac{1 - \cos(2\theta t)}{2} \quad (18).$$

Upon understanding the general formalism of investigating the force and the corresponding torque acting on a laser-polariton interacting system and the transition probability of finding the resulted system in the excited state, the readers may consider themselves ready to dive into the fully quantum behavior of the system of polariton interacting with various polarized laser radiation than the PEMM, under the influence of a magnetic field which we have considered in this study as a trap. No matter the PEMM (Eq.19) has been already considered by authors of Refs. [32, 33], we find more interesting to reconsider their results in the present study, so that the effect of other polarized laser mode including the PPEM (Eq.20), TEM (Eq.21) and the TMM (Eq.22), in study of the dynamic of the polariton interacting of laser radiation will be observed and analyzed by readers with kind attention.

$$\begin{cases} \hat{E} = \left(E_{0x} \exp(-ikz), E_{0y} \exp(-ikz), 0\right) \\ \hat{B} = \left(B_{0x} \exp(-ikz), B_{0y} \exp(-ikz), 0\right) \end{cases} \quad (19),$$

$$\begin{cases} E = \left(E_{0x} \exp(-ikz), 0, -iE_{0z} \frac{1}{k} \frac{\partial u}{\partial y} \exp(-ikz) \right) \\ B = \left(0, B_{0y} \exp(-ikz), -iB_{0z} \frac{1}{k} \frac{\partial u}{\partial y} \exp(-ikz) \right) \end{cases} \quad (20),$$

$$\begin{cases} E = \left(E_{0x}\exp(-ikz), E_{0y}\exp(-ikz), 0\right) \\ B = \left(-B_{0f}\exp(-ikz), B_{0u}\exp(-ikz), -iB_0\frac{1}{k}\left(\frac{\partial f}{\partial x} - \frac{\partial u}{\partial y}\right)\exp(-ikz)\right) \end{cases} \quad (21),$$

$$\begin{cases} E = \left(E_{0x}\exp(-ikz), -E_{0y}\exp(-ikz), iE_{0z}\frac{1}{k}\left(\frac{\partial u}{\partial y} - \frac{\partial f}{\partial x}\right)\exp(-ikz)\right) \\ B = \left(B_{0x}\exp(-ikz), B_{0y}\exp(-kz), 0\right) \end{cases} \quad (22).$$

With the PEMM (Eq.19), authors of Ref. [32] obtained the relations in Eq.23 for the force, Eq.24 for corresponding torque and Eq.25 for transition probability of funding the system in the excited state. In Eq.23-Eq.25, the subscript indicates the plane electromagnetic mode laser.

$$\overline{F_{PEML(Z)}} = \overline{F_{PEML(Lz)}} = \frac{\omega_R^2}{4\theta}k\sin(2\theta t) \quad (23).$$

$$\overline{N} = \overline{N_{PEML(z)}} = \frac{1}{2}I_m\left\{(\alpha E_x)^* E_y - (\alpha E_y)^* E_x\right\} = \frac{\overline{\mu^2}}{4\theta}\left(E_x^* E_y - E_y^* E_x\right)\sin(2\theta t) \quad (24).$$

$$P_{PEML} = \frac{\omega_R^2}{4\theta^2}\frac{1-\cos(2\theta t)}{2} \quad (25).$$

Following the same theoretical approach, we obtained the expressions in Eq.26 for the force, Eq.27 for the corresponding torque and Eq.28 for the transition probability of the system to be found in the excited state for the case of PPEM laser field (Eq.20). In the case of TEM (Eq.21), we obtained Eq.29 for the force, Eq.30 for the corresponding torque and Eq.31 for transition probability of finding the system of laser cooled and trapped polariton in the excited state. Finally, when it comes to TMM, we simply observe that from the expressions of the laser radiation Eq.22, the electric field and the magnetic field are symmetric for TEM and that of TMM. Physical interpretation, which results from the symmetry between TEM and TMM lasers, known as the electromagnetic duality, is that Maxwell's equations are invariant under the exchange of electric and magnetic fields. This physical essence behind the symmetry between TEM and TMM lasers conducts to the same parameters of physical parameters of polariton-laser interaction, i.e. force and corresponding torque, transition probability of finding the system in the excited state, and so far the total energy of the system, when performing cooling and trapping processes with laser radiations. In addition, the similarity between the results from TEM and TMM lasers implies that the dynamic of polariton can be controlled with these laser radiations by designing the cavity or waveguide accordingly. However, beneath this similarity, the symmetry between TEM and TMM lasers can have considerable physical implications in practice.

$$\overline{F_{PPL(z)}} = \frac{1}{2}\mathrm{Re}\left\{(\alpha E_{0u})^* E_0\frac{\partial u}{\partial z}\right\} = \frac{\partial}{\partial z}\frac{\alpha^{'}|E|^2}{4} \quad (26),$$

$$\overline{N} = \overline{N_{PPL(y)}} = \frac{1}{2}\mathrm{Im}\left\{\mu_z^* E_x - \mu_x^*\right\} = \frac{1}{2}\frac{\overline{\mu^2}}{2\theta}\left(E_z^* E_x - E_x^* E_z\right)\sin(2\theta t) \quad (27),$$

$$P_{PPL} = \frac{\partial}{\partial z}\frac{\overline{\mu^2}|E|^2}{16\theta}\frac{\delta}{\theta}\left\{\frac{1}{2\theta}\sin(2\theta t) - t\right\} \quad (28),$$

$$\overline{F_{TEM(z)}} = \frac{1}{2}\mathrm{Re}\left\{\dot{\hat{\mu}}^{*} B_y - \dot{\hat{\mu}}^{*} B_x\right\} = \frac{1}{2}\frac{\omega_R^2}{2\theta} k \sin(2\theta t) \tag{29}$$

$$\overline{N} = \overline{N_{TEM(z)}} = \frac{1}{2}\mathrm{Im}\left\{\mu_x^* E_y - \mu_y^* E_x\right\} = \frac{1}{2}\frac{\overline{\mu^2}}{2\theta}\left(E_x^* E_y - E_y^* E_x\right)\sin(2\theta t) \tag{30}$$

$$P_{TEM} = k\,\frac{\omega_R^2}{4\theta^2}\,\frac{1-\cos(2\theta t)}{2} \tag{31}$$

To make the comparison transparent and reveal where the differences come from, we summarized in Table 1 the expressions for force, torque and transition probability for the four types of laser-polarized modes.

Table 1 Comparison of the forces, torque and transition probabilities for the four types of laser-polarized modes.

Laser-polarized mode	**Force**	**Torque**	**Transition Probability**
PEMM	$\frac{\omega_R^2}{4\theta} k \sin(2\theta t)$	$\frac{\overline{\mu^2}}{4\theta}\left(E_x^* E_y - E_y^* E_x\right)\sin(2\theta t)$	$\frac{\omega_R^2}{4\theta^2}\frac{1-\cos(2\theta t)}{2}$
PPEM	$\frac{\partial}{\partial z}\frac{\alpha' \lvert E\rvert^2}{4}$	$\frac{1}{2}\frac{\overline{\mu^2}}{2\theta}\left(E_z^* E_x - E_x^* E_z\right)\sin(2\theta t)$	$\frac{\partial}{\partial z}\frac{\overline{\mu^2}\lvert E\rvert^2}{16\theta}\frac{\delta}{\theta}\left\{\frac{1}{2\theta}\sin(2\theta t) - t\right\}$
TEM	$\frac{1}{2}\frac{\omega_R^2}{2\theta} k \sin(2\theta t)$	$\frac{1}{2}\frac{\overline{\mu^2}}{2\theta}\left(E_x^* E_y - E_y^* E_x\right)\sin(2\theta t)$	$k\,\frac{\omega_R^2}{4\theta^2}\frac{1-\cos(2\theta t)}{2}$
TMM	$\frac{1}{2}\frac{\omega_R^2}{2\theta} k \sin(2\theta t)$	$\frac{1}{2}\frac{\overline{\mu^2}}{2\theta}\left(E_x^* E_y - E_y^* E_x\right)\sin(2\theta t)$	$k\,\frac{\omega_R^2}{4\theta^2}\frac{1-\cos(2\theta t)}{2}$

3. Results and discussion

In this section, we present numerical analysis of theoretical results obtained above. Let remind to readers that the aim of this study is to investigate the behavior of a system of polariton interacting with various polarized laser radiation and perform comparison for a proper choice of the best laser polarized mode for realizing both theoretical and practical studies based on light-polariton interactions. For this analysis, still we consider the approximations made by [32]. Specifically, we assume that $E_x^* = E_y$ and $E_y^* = -E_x$. The theoretical approach used in this paper and particularly the consideration of the RWA imposes to set the laser frequency equal to the Rabi frequency $(\omega_{Rabi} = \mu E_0)$ given that E_0 is the amplitude of the radiation field, no matter some implications that the model's limitations may have on the results. Another reason of setting the laser frequency as being equal to Rabi frequency is due to the fact that the present study is the continuity of the published work [32] where the oscillatory state was taken at the resonance and equal to the Rabi frequency. Therefore, considering the same system with identical parameters, we just adjust at time to time a particular laser polarized mode and observed it effect on a moving polaritonic entity. So far, the fact that the polariton is addressed in the present study as the single particle, without any interactions neither with other atomic entities in the system nor with the surrounding environment, requires the consideration of laser radiation frequency equals to Rabi frequency in order to ease the study. In real situation, the consideration that laser frequency is equal to Rabi frequency may enhances the laser/polariton interaction thereby conducting to the possibility for the realization of Bose-Einstein condensation of polaritons. We consider all parameters as dimensionless parameters, i.e. no unit is assigned to any parameter in the system. Following our previous studies [32, 33], we set the coupling strength constant $g = 0.35$ for low interaction laser/particle and $g = 1.6$ for strong interaction. For various curves, we have chosen the component of the dipole moment along the direction of the light $\mu = 0.3$ and the laser amplitude $E_0 = 0.5$.

Following the idea of [32], we limit ourselves to numerical investigation of the force (FIG.3 and FIG.4), torque (FIG.5 and FIG.6) and transition probability (FIG.7 and FIG.8). For these figures, physical parameters including force, torque and transition probability) are numerically illustrated as a function of time t (FIG.3, FIG5 and FIG.7) and Rabi frequency (FIG.4, FIG.6 and FIG.8) respectively. FIGs.3-7 are plotted for different values of coupling strength constant g , i.e. $g = 0.35$ (low coupling strength with surrounding environment) and $g = 1.6$ (strong coupling strength with surrounding environment). From the graphical interpretation of FIGs.3-7, we decided to depict the graphical representation of the transition probability versus time at low coupling strength constant with surrounding environment ($g = 0.35$).

We depicted the graphical representation of the force applied on the polariton versus time (FIG.3) and Rabi frequency (FIG.4) for low $(g = 0.35)$ (a) and strong $(g = 1.6)$ (b) coupling strength constant. Both FIG.3 and FIG.4 present an array of sinusoidal waves, characteristic of the system's coherent state. This is an exotic phenomenon that relates quantum optics to classical optics and vice-versa. In physics, coherent states play an important role in representing quantum dynamics, particularly when the quantum evolution is close to classical [55]. A paradigmatic research with coherent states is demonstrating quantum-classical correspondence, which addresses how classical behavior of a system develops to quantum mechanically [56]. The observation above reveals that, no matter the semi classical approach used in the study of the dynamic of the polariton interacting with laser radiation, numerical result interpretations and discussions can be extended to quantum mechanical behavior of the resulted light/matter(polariton) interacting system. This observation stands as a reason not only to describe the present research work as an analysis of forces/torques and excited-state dynamics in different field configurations, but also to use at ease laser cooling and trapping of polariton terminologies as depicted in FIG.2d. In FIG.3 and FIG.4, the intensity of the force acting on the laser cooled and trapped polaritonic system is greater in the case of PPEM laser than other laser polarized mode such as PEMM, TEM and TMM lasers. Physical interpretation that arises from this observation is that the PPEM laser is the best optical trap that confines polaritonic entities in the system. Strong interaction between light and polariton conducts to the destruction of the coherent state of the system as shown in FIG.3b and FIG.4b, thereby predicting the use of PPEM laser radiation at low coupling strength constant $(g = 0.35)$ in light/matter(polariton) interaction experiments. In addition, the form of the curves of FIG.3a looks alike with those of FIG.1 obtained by authors of Ref. [57]. Stimulated by the above similarity, we can assume that the amplitude of the forces (FIG.3a) collapses and expands in turn as a manifestation of its nonstaticity like the behavior of the Fock-state nonstatic waves. Yield the possibility to study the characteristics of nonstatic quantum light waves in the environment of cooled and trapped polaritonic entities with a wide range of scientific and technological applications [57, 58].

In FIG.5 and FIG.6, we illustrate graphically the corresponding torque versus time (FIG.5) and Rabi frequency (FIG.6). Still, all the curves present Rabi oscillations that correspond to coherent state of the system, a result which is similar to that of [59]. Upon observing FIG.6, it can be discerned that the dynamic of the polariton interacting with laser radiation is associated with it rotational tendency within the range of laser influence. The tangential direction of the laser cooled and trapped polariton's movement constitutes the direction of radiation. At the beginning of the cooling and trapping process, i.e at the beginning of light/matter(polariton) interaction, the polariton's movement is relatively unstable and the movement direction undergoes rapid changes, resulting in a relatively sluggish population transfer from the excited state to the ground state. As the laser (Rabi) frequency increases, the polariton's movement is relatively stable, thereby enabling the fast population transfer from the excited state to the ground state within a very narrow angle range. In case of choosing the best laser polarized mode to be used for realizing both theoretical and practical studies based on light-matter interactions, our result is different to the observation made in the case of force. For instance, the difference does not have any effect on the conclusion. In fact, FIG.5 indicates that the orientation chose and the rotation of the particle do not really alter the cooling process as suggested [32]. Although theoretical demonstration made by [32], the effects are not too consistent.

FIG.7 examines the influence of transition probability with respect to Rabi frequency. FIG.7 shows that the transition probability for the system to be find in the excited state is notably influenced by the laser frequency. It can be seeing that, as the laser frequency increases continuously, the probability of the system to be find in the excited state keeps reducing, and tends to zero at very intense laser frequency. This is due the fact that an increase in laser frequency intensifies the force applied on the system of polariton more vigorously, leading to a system at rest. More specifically, at the beginning of the interaction between laser radiation and the polariton, the probability of finding the system of polariton in the excited state is predominantly distributed in the high-value region. This is because at the beginning of light/polariton interaction, the laser frequency is relatively small, the force applied on the system for reducing its motion is low, and the corresponding torque is relatively low. As the laser frequency increases with time of light/matter interaction, the transition probability of finding the system in the excited state decreases progressively, resulting to population inversion, up to a certain value of laser frequency (cutoff frequency), where we observe complete population transfer from excited state to ground state. This implies that we achieved a new macroscopic quantum state of the system where the energy is mainly concentrated. This new state of the system is what we call polariton condensates nomatter the fact that our approach does not properly takes into account the presence of semiconductor microcavity. The above observations indicate that the formation of polariton condensates occurs more rapidly in the week coupling regime where the cutoff frequency is 7 (FIG.7a), compared to the strong coupling regime where the cutoff frequency is above the value 10 (FIG.7b). This means that the interaction between the laser radiation and polaritonic quasiparticles is significantly more reliable in the week coupling regime $(g = 0.35)$ and at high laser frequency. From the coherent state of the system observed above, the resulted polariton condensates exhibit the properties similar to those observed in coherent optics [60]. Polariton condensates have been obtained by several authors in their studies based on light/matter(polariton) interaction [61, 62, 63]. With samples of polariton condensates, Plasma physics at the extremely low temperature limit has become possible and long ranging correlations arising from the Coulomb interaction can be studied. Aside from being the testing ground and the ideal tool for the demonstration of fundamental concepts and ideas, polariton condensates have become the workhorse for many modern precision measurements, and they stand as appropriate candidate for future technologies.

In the former section, as we observed that the interaction between laser radiation and polariton is more suitable in the week coupling regime $(g = 0.35)$ and at high laser frequency, we depicted in FIG.8, graphical representation of transition probability versus time at low regime light/matter (polariton) interaction. FIG.8 reveals that the transition probability grows and then drops down to zero. This cycle continues until the light field is switched off entirely. Incidentally, when we say that the transition probability of finding the system in the excited state drop down to zero, we also simultaneously imply that the ground state population increases. FIG.8 shows that the transition probability amplitude of finding the laser cooled and trapped polariton in the excited state is less pronounced under PPEM mode laser radiation. This confirms our hypothesis made above, were we have predicted that laser cooling and trapping of polariton is more appropriate under PPEM laser radiation than other polarized modes. No matter the identity in theoretical results between TEM and TMM laser radiations, consistent differences are observed in numerical result based on the transition probability of finding the polaritonic entities in the excited state when they are cooled and trapped with these polarized laser radiations. This observation truly justifies our hypothesis made above in the previous section regarding physical implications the symmetry between TEM and TMM lasers may have both in theory and in practices. The explanation that arises from the observed difference is that these laser polarized mode represent beams based on complex sink-source combinations of either electric or magnetic dipoles oriented along the z axis. Therefore, each of the laser polarized beam might have different effect on the cooled and trapped polariton. Understanding these effects is crucial for designing and optimizing various photonic devices such as laser resonators, optical waveguides and photonic crystals. Seeking to bridge the gap results an interesting research perspectives. For instance, the cooling and trapping processes of polaritons are more pronounced in the case of PPEM. Thus, laser cooling and trapping of polariton conducts to interference patterns. In other words, laser cooling and trapping of polariton predicts coherent population transfer from excited state to ground state. This confirms the first observation made above. The interference fringes observed are well explained by the high value ground state energy and the conservation of the magnitude of the fringe visibility is a direct result of low dephasing. Another interpretation which arises from FIG.8 is that the laser cooled and trapped polariton exhibits Rabi oscillations, which means that, in accordance to authors of Ref. [33], laser cooling and trapping of polariton can help to realize and stabilize the degree of entanglement between the atom and the field at a high level. Entanglement is a linchpin of quantum computing and information processing [64, 65]. The entanglement of multipartite systems is a necessary requirement for efficient quantum computing, without which it would not be sufficient to gain computational advantage over classical computing methods [66]. This confirms the fact that laser cooled and trapped polaritonic entities are potential candidates for successful implementation of quantum computers.

Overall, FIG.3 to FIG.8 exhibit a sine-squared waveform. This waveform is not surprising since [30] obtained identical waveform both for force and corresponding torque acting on a laser cooled and trapped polariton and transition probability of finding the system of cooled and trapped polariton in the excited state. In general, following the research studies of authors of Refs. [21, 22], graphical schematization of laser cooled and trapped polariton's physical parameters including force, torque and transition probability for the case of this study depends on the manner in which the light field perturbation varies over time. On closer inspection, we can extract significant physical aspects about the light-polariton interaction from the sine-squared waveform distribution obtained in FIGs.3-8. From these figures (FIG.3-FIG.8) and following the analysis of authors of Ref. [32], we can infer that the force, the torque and the transition probability of finding the system in the excited state oscillate at the Rabi frequency. This means that, from the viewpoint of dynamic, the entire laser cooled and trapped polaritonic system is in resonance with the laser radiation. Yield Rabi oscillations in the system which reveals complex features at the mesoscopic scale. Authors of Ref.[59] also indicate in their study based on nonlinear coherent mode and atom optics the observation of Rabi oscillations. Such a deduction comes from the fact that these physical parameters, i.e. the force and corresponding torque and transition probability depend on the state amplitudes, themselves also oscillate at the Rabi frequency. This is an indication of the highly cooled and trapped nature of the polariton. In fact, at the resonance, the polaritonic system absorbs energy from the laser radiation used for the cooling and trapping process. The vibrational energy stored by the polaritonic system conducts to coherent population transfer from excited state to ground state as it is shown in FIG.3. The resulted four state system are crucial for various quantum information processing tasks such as potential room temperature operation, incorporation of non-equilibrium physics, strong nonlinearity, quantum simulation, interferometry, information processing, non-classical state generation [67] and the generation of nonlinear coherent modes in polariton condensates [59] to cite just these few [67]. Moreover, Rabi oscillations observed in the system are of probability amplitudes and therefore correspond to a strongly quantum mechanical phenomenon, that involves maximally entangled states. In FIG.3b, we observe a considerable number of vacuum Rabi periods as compared to FIG.3a. This result is an indication of the destruction of the coherent state of the system due to interactions with the environment. It comes that the laser's effect is negligible in the strong coupling regime between the system and surrounding environment. This is evident in the torque (FIG.4) where the stability of the cooled and trapped polariton is more pronounced at low coupling with surrounding environment (FIG.4a). The interpretation above stands as another reason why we consider graphical representation of transition probability of founding cooled and trapped polaritonic entities in the excited state versus time only at low coupling with surrounding environment (FIG.5).

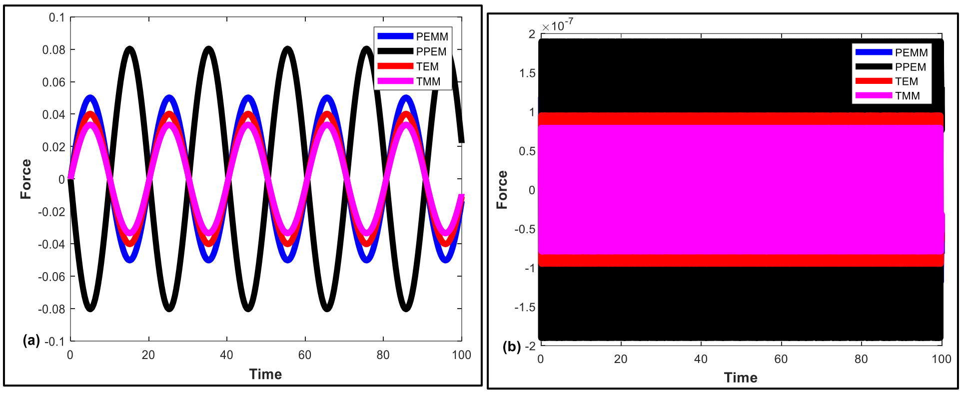

Figure 3 Force versus time for low $(g = 0.35)$ (a) and strong $(g = 1.6)$ (b) coupling strength constant. We choose $\Delta = 1.42$, $k = \omega = 0.5$. The figure shows the retention force applied by various laser mode oppositely on the moving polariton in semiconductor micro-cavity. In both low and strong coupling light/matter regime, the intensity of the mechanical force applied on the system is higher for PPEM laser radiation that other laser polarized modes

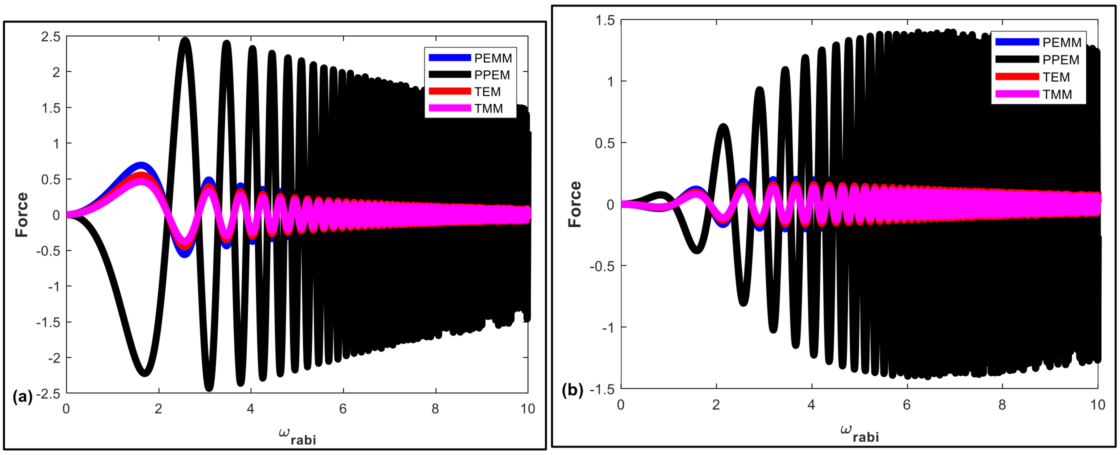

Figure 4 Representation of Graphical the force versus Rabi frequency

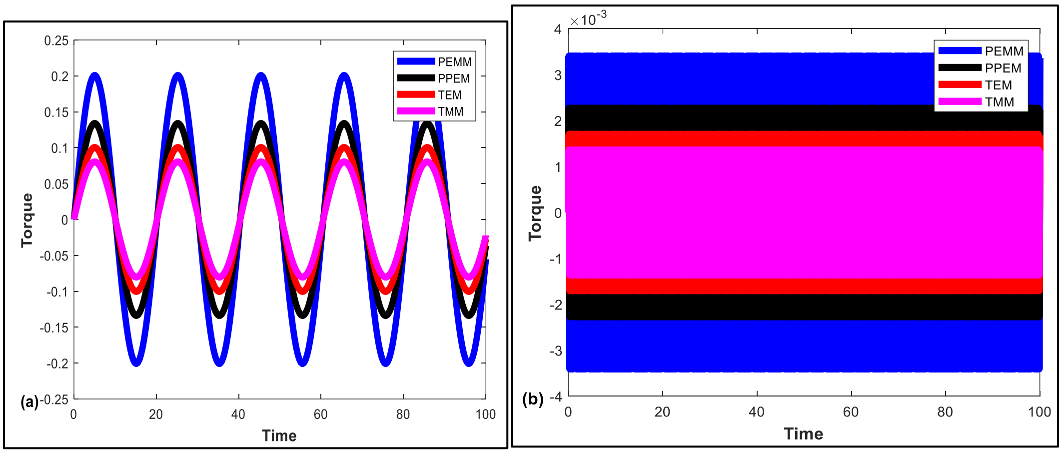

Figure 5 Torque versus time for low $(g = 0.35)$ (a) and strong $(g = 1.6)$ (b) coupling strength constant. We choose $\Delta = 1.42$, $k = \omega = 0.5$. Here, we depicted numerically the rotational force applied by various laser modes on the moving polariton in semiconductor micro-cavity. These forces that causes the moving polariton in semiconductor microcavities to change its rotational motion are more appreciated when it comes to PEMW laser radiation.

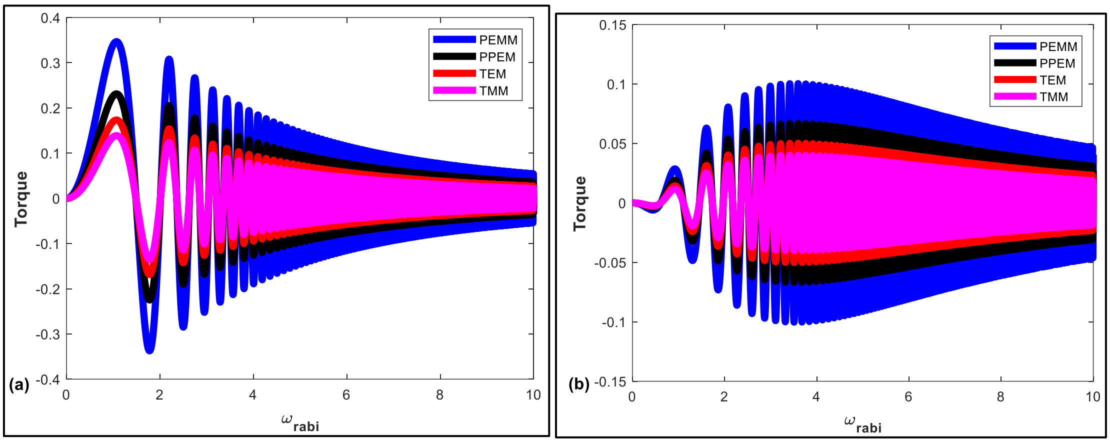

Figure 6 Graphical representation of the torque versus Rabi frequency for both low (a) and strong (b) coupling strength constant

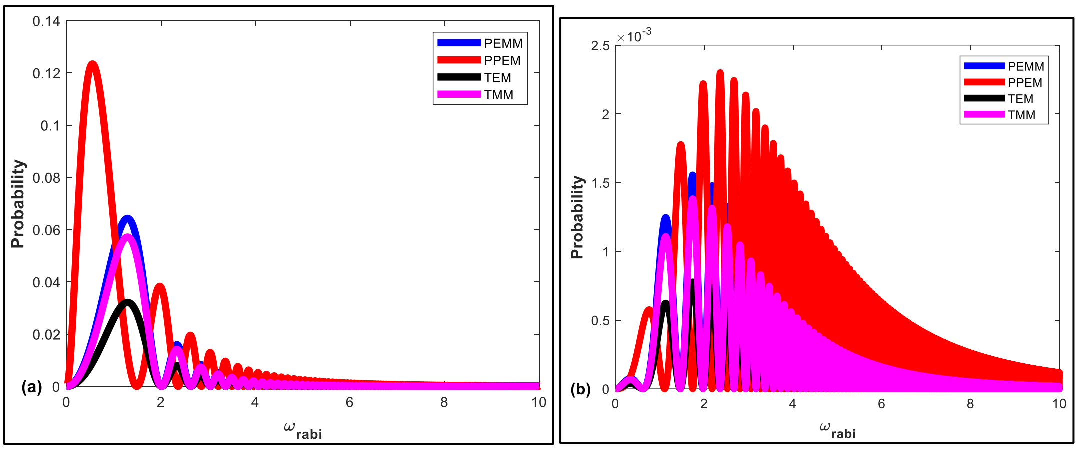

Figure 7 Transition probability versus Rabi frequency at low (a) and strong (b) coupling light/matter interaction when $\Delta = 1.42$ and $k = 0.5$. Due to light/matter interaction, the transition probability of finding the system of laser cooled and trapped polaritonic entity in the excited state in semiconductor microcavity is less pronounced when light/interaction is accomplished with PPEM laser radiation. This shows that PPEM laser mode is the one that can bring polaritons at rest during interaction

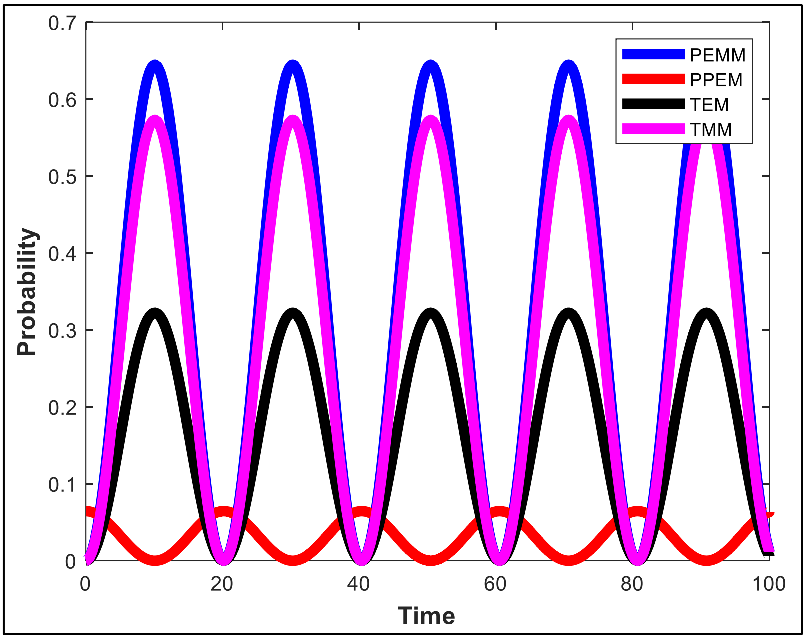

Figure 8 Transition probability versus time

4. Conclusion

In summary, this study investigated the effect of different types of laser-polarized modes on the dynamic of polaritons under the influence of magnetic field, in order to recommend to the scientific community the best laser-polarized mode for realizing both theoretical and practical studies based on light-matter interactions. We used semi-classical approach under RWA to calculate the most important physical parameters including the force and its corresponding torque and the transition probability of finding the system of laser cooled and trapped polariton in the excited state. Our results clearly indicate that despite significant findings from previous studies, cooling and trapping polaritonic quasiparticles is well achieved under PPEM laser radiation than other laser-polarized mode such as PEMM, TEM and TMM. This study stands as a foundation for many other research works for the formal recommendation of the best laser-polarized mode to be use when both theoretical and practical studies based on light-polariton interactions in nanostructures microcavities are carried. Therefore, our interest for future research studies go to the following topics: (i) Assessing the impact of s/p-polarized and/or phase difference of E-field on cooling and trapping of polartions; (2i) Investigating complex propagation constants of polaritons cooled and trapped with s/p-polarized and/or phase difference of E-field; (3i) Experimental investigation of the effect of different polarized laser radiation on cooling and trapping of polariton: a complementary study; (4i) Cooling and trapping of polariton with TEM and TMM lasers: observing the double effect and finally (5i) dynamical analysis of laser cooled and trapped polariton with Bloch and/ Lindblad equations.

Compliance with ethical standards

Disclosure of conflict of interest

The authors declare no competing interests.

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