Enhancement of quantum synchronization in optomechanical system by modulating the couplings

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Keywords: optomechanical systems, two switches, periodic modification, quantum synchronization

Abstract
We study two coupled optomechanical systems interact mutually through an optical fiber and a phonon tunneling, which are controlled by two switches $K_1$ and $K_2$. Compared to the quantum synchronization of the optomechanical systems without modification, we find that a proper periodic modification by different switches setups can achieve a better quantum synchronization. In addition, we also analyze the robustness of the periodically modified system against the bath’s mean temperature or the oscillators’ frequency difference, respectively.

1. Introduction

As a very fascinating phenomenon in classical physics, synchronization has played an important role in the research on many fundamental issues, e.g. neuron networks [1, 2], chemical reactions [3], heart cells [4], etc. With the progress in communications technology, physics system is required to ensure a higher degree of synchronization in order to guarantee the reliable information transmission. Therefore, the synchronization has been widely applied in the field of control and communication.

In recent years, many efforts have been devoted to bring this interesting phenomenon into quantum regime. Mari et al proposed a scheme to generalize the classical synchronization concept to quantum system and measured the complete synchronization and phase synchronization in the continuous variable (CV) system [5]. Consequently, this work has rapidly met the increasing interest of quantum synchronization in many kinds of systems, such as optomechanics [6, 7], cavity quantum electrodynamics [8, 9], atomic ensembles [10–12], van der Pol (VdP) oscillators [13–17], Bose–Einstein condensation [18], superconducting circuit systems [19, 20], and so on. Moreover, the schemes of realizing quantum synchronization are also proposed both experimentally [21–25] and theoretically [26–31]. Remarkably, a lot of new researches and achievements have emerged recently [32–34].

According to the previous studies, there are two ways to realize the synchronization between the two mechanical oscillators. One way is the mutual exchange of energy between the two oscillators [5, 35, 36], and the other way is controlling the system by external fields [35–39]. The two mechanical oscillators will trend to synchronize after a long period of time and synchronization is very sensitive to many parameters in optomechanical systems, such as coupled intensity, driving field, temperature and so on. In particular, it has been found that the quantum synchronization can be enhanced by periodically modulating some parameters of the system [40, 41]. Farace et al proposed that periodic modifications can be applied to improve the quantum effects in optomechanical systems [40]. In addition, Mari et al and Chen et al proved that modifications can also enhance the quantum entanglement in optomechanical systems, respectively [42, 43]. Therefore, we want to study whether quantum synchronization can be enhanced by time-periodic modulations.

In this paper, based on the previous work [44] which used the Mari’s method, we study the quantum synchronization controlled by different logical relationships of two switches (open or closed) of coupling between two mechanical oscillators. We realize two cases by controlling the switches: one is that the two mechanical oscillators are indirectly coupled [37, 45, 46] and the other is that the two mechanical oscillators are
directly coupled [5, 35, 36]. By including the periodically modulating cavity detunings, the quantum synchronization can be greatly enhanced.

This paper is organized as follows. In section 2, we introduce the model and the methods, especially the method of measuring the quantum synchronization. In section 3, periodic cavity-modulation schemes of two cases are proposed and the quantum synchronization degree is analyzed. Furthermore, we compare the stability of cavity-modulation schemes by studying the robustness of the bath’s mean temperature and the eigenfrequency difference. Conclusions are given in section 4.

2. Model and methods

In order to show the enhancement of the quantum synchronization [37] via the periodic modification, we choose a controlled quantum synchronization model which is designed based on the quantum optomechanical system as shown in figure 1. Here, we focus on a single-mode electromagnetic field coupling to the mechanical motion of the moving mirror via the radiation-pressure coupling in each cavity. Without loss of generality, we assume that the two optomechanical cavities are identical and driven by the same lasers with intensity $E$. The couplings between the two optomechanical systems are realized by a fiber with coupling constant $\lambda$ [36, 45] and a phonon tunnel with intensity $\mu$ [5, 35, 36], which are controlled by the switches $K_1$ and $K_2$ [35], respectively. Therefore, the quantum synchronization control can be realized through different logical relationships of the two switches $K_1$ and $K_2$. The switches $K_1$ and $K_2$ can change $\lambda$ and $\mu$ values from zero to a positive constant by turning the switches on and off [35]. To better the performance of the scheme, periodic modulations on the eigenfrequency of each cavity [47] are introduced.

In the rotating frame, the Hamiltonian of this model can be written as ($\hbar = 1$):

$$H = \sum_{j=1,2} \left\{ -\Delta_j(1 + \epsilon_j \cos(\Omega_j t))a_j^\dagger a_j + \frac{\omega_{mj}}{2}(p_j^2 + q_j^2) - g a_j^\dagger a_j q_j + iE(a_j^\dagger - a_j) \right\} - \mu q_2 a_2 + \lambda(a_1 a_2^\dagger + a_2 a_1^\dagger),$$

(1)

where $\Delta_j = \omega_L - \omega_{mj}$ refers to the detuning of the laser driving to the cavity mode [5, 35–37], and $\omega_{mj}$ are the mechanical eigenfrequencies assumed to be slightly different with each other. The operators $a_j$ and $a_j^\dagger$ are the creation and annihilation operators for the optical field, satisfying $[a_j, a_j^\dagger] = \delta_{ij}(j = 1, 2)$. $q_j$ and $p_j$ are dimensionless position and momentum operators of the $j$-th mechanical oscillator satisfying $[q_j, p_j] = i\hbar$. $g$ is the optomechanical coupling constant. The piezoelectric transducer can convert the electrical signal to mechanical vibration. We can use it to achieve the periodic modifications of cavity lengths, so as to realize the periodic modifications on the cavity frequencies and the detunings [47]. $\epsilon_j$ is the amplitude of modulations we appended on cavities, and $\Omega_j$ is the frequency of the modulations correspondingly. In calculation, the damping rates and the intensity of the driving field are assumed to be equal in both cavities, while the frequencies and initial conditions of the two cavities are different. Compare to the former relevant work [5], we properly reduce the intensity of the driving field in order to highlight the coupling function in synchronization, since a too-strong driving field will weaken the coupling effect and lead to the ‘forced’ synchronous effect.

Next, we take dissipation effects into consideration. The quantum Langevin equations (QLE) of our system in Heisenberg picture [48, 49] can be written as
\[ \dot{q}_j = \omega_m p_j, \]
\[ \dot{p}_j = -\omega_m q_j + g a_j^\dagger a_j + \mu q_{3-j} - \gamma_m p_j + \xi_p, \]
\[ \dot{a}_j = -\left( \kappa - i\Delta_j(1 + \varepsilon \cos(\Omega_j t)) \right) a_j + i g a_j q_j + E - i\lambda a_{3-j} + \sqrt{2\kappa} a_j^{\text{in}}. \]  

Here, \( \kappa \) is the decay rate of the optical cavities, and \( \gamma_m \) represents the damping rate of the mechanical oscillators which is inversely proportional to quality factor \( Q \). \( a_j^{\text{in}} \) is the radiation vacuum input noise operator which satisfies the autocorrelation function \( \langle a_j^{\text{in}}(t) a_j^{\text{in}}(t') \rangle + \delta_j \delta(t - t') \). The Brownian noise operator \( \xi_p \) satisfies the correlation relation \( \frac{1}{2} \xi_j(t) \xi_j(t') + \xi_j(t) \xi_j(t') = \gamma_m (2n_b + 1) \delta_j \delta(t - t') \) under Markov approximation, where \( n_b = \left[ e^{\kappa_{\text{m}}/k_B T} - 1 \right]^{-1} \) is the mean phonon number of the mechanical bath which is determined by the environment temperature \( T \) \cite{50-52}.

Since it is difficult to solve equation (2) analytically, we introduce the mean-field approximation to simplify the calculations by rewriting the system variable operators as the sum of a c number mean value and a small fluctuation near the mean value, i.e.

\[ q_j(t) = \langle q_j(t) \rangle + \delta q_j(t), \]
\[ p_j(t) = \langle p_j(t) \rangle + \delta p_j(t), \]
\[ a_j(t) = \langle a_j(t) \rangle + \delta a_j(t). \]

Because of the presence of random noise, the mean values are much bigger than the fluctuations. Therefore, by substituting equation (3) into (2), the QLE equation can be approximately divided into the zero-order mean value terms and the first-order quantum fluctuation terms. Then we get two different sets of equations. One for the expectation values reads,

\[ Q_j = \omega_m p_j, \]
\[ \dot{P}_j = -\omega_m Q_j + g |A_j|^2 + \mu Q_{3-j} - \gamma_m P_j, \]
\[ A_j = -\{ \kappa - i\Delta_j(1 + \varepsilon_j \cos(\Omega_j t)) \} A_j + ig A_j Q_j + E - i\lambda A_{3-j}. \]  

And one for the quantum fluctuation reads,

\[ \dot{b}_j = \omega_m b_j, \]
\[ \dot{\delta p}_j = -\omega_m \delta q_j + g (A_j^* \delta a_j + A_j \delta a_j^*) + \mu \delta q_{3-j} - \gamma_m \delta p_j + \xi_p, \]
\[ \dot{\delta a}_j = -\{ \kappa - i\Delta_j(1 + \varepsilon_j \cos(\Omega_j t)) \} \delta a_j + ig (A_j \delta q_j + Q_j \delta a_j) - i\lambda \delta a_{3-j} + \sqrt{2\kappa} \delta a_j^{\text{in}}. \]

By introducing the transforms \( x_j = \frac{a_j + a_j^\dagger}{\sqrt{2}}, \)
\[ y_j = \frac{a_j - a_j^\dagger}{\sqrt{2}i}, \]
for the creation and annihilation operators and \[ x_j^{\text{in}} = \frac{a_j^{\text{in}} + a_j^{\text{in}}^\dagger}{\sqrt{2}}, \]
\[ y_j^{\text{in}} = \frac{a_j^{\text{in}} - a_j^{\text{in}}^\dagger}{\sqrt{2}i}, \]
for the input noise operators, equation (5) can be rewritten into a more compact form,

\[ \dot{u} = Su + n \]

with vector \( u = [u_1, u_2, u_3, u_4, u_5, u_6, u_7]^T = [\delta q_1, \delta p_1, \delta x_1, \delta y_1, \delta q_2, \delta p_2, \delta x_2, \delta y_2]^T \) and the noise column vector \( n = (0, \xi_j, \kappa, 0, \xi_j, \kappa, 0, \xi_j, \kappa)^T \).

\[ S = \begin{pmatrix} S_1 & S_0 \\ S_0 & S_2 \end{pmatrix} \]

is an \( 8 \times 8 \) time-dependent matrix with

\[ S_{1,2} = \begin{pmatrix} 0 & \omega_{m,1,2} & 0 & 0 \\ -\omega_{m,1,2} & -\gamma_m & \sqrt{2}g \Re(A_{1,2}) & \sqrt{2}g \Im(A_{1,2}) \\ -\sqrt{2}g \Im(A_{1,2}) & 0 & -\kappa & -\Delta_{1,2}(1 + \varepsilon_j \cos(\Omega_{1,2} t)) + gQ_{1,2} \\ \sqrt{2}g \Re(A_{1,2}) & 0 & \Delta_{1,2}(1 + \varepsilon_j \cos(\Omega_{1,2} t)) + gQ_{1,2} & -\kappa \end{pmatrix} \]

and

\[ S_0 = \begin{pmatrix} 0 & 0 & 0 & 0 \\ \mu & 0 & 0 & 0 \\ 0 & 0 & \lambda & 0 \\ 0 & 0 & -\lambda & 0 \end{pmatrix}. \]

With the evolution of the expectation values and the quantum fluctuations, we next study the quantum synchronization in the mean field treatment. The error operators \( q_j(t) \) and \( p_j(t) \) of the position and
momentum operators operators $q_j(t)$ and $p_j(t)$ between the two mechanical oscillators can be defined as follows,

$$\begin{align*}
q_j(t) &= \frac{1}{\sqrt{2}} [q_1(t) - q_2(t)], \\
p_j(t) &= \frac{1}{\sqrt{2}} [p_1(t) - p_2(t)].
\end{align*}$$

(10)

It is easy to find that the quantum complete synchronization [5] will be realized when both $q_j(t)$ and $p_j(t)$ asymptotically vanish as they evolve. However, these two error operators can not have zero values simultaneously due to the Heisenberg uncertainty relation. Hence, the quantum complete synchronization has a bound which is distinct from the classical synchronization. For this reason, we introduced the following figure of merit [5] based on

$$S_c(t) = \langle q_j^2(t) + p_j^2(t) \rangle^{-1}$$

(11)

to measure the quantum complete synchronization. This is a valid metric for genuine quantum synchronization since both of the influence of quantum fluctuation and nonlocal quantity are considered in this synchronization measure. The classical synchronization (even in quantum system) and genuine quantum synchronization can also be effectively distinguished. Following the Heisenberg uncertainty relation $\langle q_j(t)^2 \rangle \langle p_j(t)^2 \rangle \geq \frac{\hbar^2}{4}$, we have

$$S_c(t) \leq \frac{1}{2\sqrt{\langle q_j(t)^2 \rangle \langle p_j(t)^2 \rangle}} \leq 1,$$

(12)

which sets a universal limit for the complete synchronization of the two CV systems. While, for a classical theory, $S_c$ does not have this upper bound. In practice, a small value of $S_c(t)$ can have two possible origins: the mean values of $q_j(t)$ and $p_j(t)$ are not exactly zero which is the same as the classical synchronization, or the fluctuations of such operators are large. If we want to investigate only the quantum effects on the synchronization, the error operators can be redefined as the relative ones:

$$\begin{align*}
q_j(t) &\to \langle q_j(t) \rangle, \\
p_j(t) &\to \langle p_j(t) \rangle.
\end{align*}$$

(13)

Obviously, the bound of equation (12) still holds for this relative measure which has the range $S_c(t) \in (0, 1]$. In our mean-field treatment (3), the relative error operator (13) takes the form

$$\begin{align*}
\delta q_j(t) &= \frac{1}{\sqrt{2}} [\delta q_1(t) - \delta q_2(t)], \\
\delta p_j(t) &= \frac{1}{\sqrt{2}} [\delta p_1(t) - \delta p_2(t)].
\end{align*}$$

(14)

Therefore, if we only consider the synchronization caused by quantum effects, the relative measure for quantum synchronization becomes

$$S'_c(t) = \langle \delta q_j^2(t) + \delta p_j^2(t) \rangle^{-1}.$$

(15)

Since the quantum fluctuation part of the QLE is stochastic, we introduce the correlation matrix to calculate the quantum fluctuations of the system variables and obtain the value of the synchronization measure. The fluctuations in the stable regime will also evolve to an asymptotic zero-mean Gaussian state. The covariance matrix we use here is defined as

$$C_q(t) = \frac{1}{2} \langle u_i(t) u_j(t^\prime) + u_j(t^\prime) u_i(t) \rangle.$$

(16)

Its evolution satisfies the linear ordinary differential equation [53, 54]

$$\dot{C} = SC + CS^T + N,$$

(17)

where $N = \text{diag} \{ 0, \gamma_{00}(2n_0 + 1), \kappa, \kappa, 0, \gamma_{00}(2n_0 + 1), \kappa, \kappa \}$ is the noise correlation satisfying $N_{00}(t - t^\prime) = \langle n_i(t) n_i(t^\prime) + n_i(t^\prime) n_i(t) \rangle$. Hence the synchronization measure can be written as

$$S'_c(t) = \left\{ \frac{1}{2} [C_{21}(t) + C_{31}(t) - 2C_{32}(t)] + \frac{1}{2} [C_{23}(t) + C_{66}(t) - 2C_{26}(t)] \right\}^{-1}.$$

(18)

By numerically solving equations (4), (6), (17), the value of the synchronization measure $S'_c(t)$ can be derived. Besides, we also calculate the time-averaged synchronization measure

$$\overline{S_c(t)} = \lim_{T \to \infty} \frac{1}{T} \int_0^T S_c(t) \, dt.$$

(19)
to include different parameters setups. It can be verified that the system is asymptotically stable according to $R = H$ criterion [35], since all the eigenvalues of the coefficient matrix $S$ will be negative after a temporary evolutionary process. Hence there will be a stable limit cycle solution representing a periodic oscillation.

3. Main results

We firstly discuss the quantum synchronization of the system without any modification. In our model, the two coupled optomechanical systems can be modulated by the switches $K_1$ and $K_2$. Thus, there are four cases as follows: (a) $K_1$ and $K_2$ are both open at the same time. In this case, the quantum synchronization can not be generated because there is no coupling between the two optomechanical systems [35]. (b) $K_1$ is closed and $K_2$ is open. In this case, our model can be simplified to two optomechanical systems that interact through an optical fiber [37, 45, 46] and the two mechanical oscillators are indirectly coupled. The quantum synchronization is not good whatever the value of parameter $\lambda$ is [45]. (c) $K_1$ is open and $K_2$ is closed. In this case, our model can be reduced to two optomechanical systems interacting through a phonon channel and the two mechanical oscillators are directly coupled, which is just the model Mari proposed [5]. The quantum synchronization is also not perfect, $\tilde{S}_q(t)$ can only reach 0.15 at the best [5, 35, 36]. (d) $K_1$ and $K_2$ are both closed at the same time. The quantum synchronization can be improved, but it is still not good enough (The maximum value of $\tilde{S}_q$ is not more than 0.15 in what Li et al studied) and the process is too fuzzy [35].

Therefore, we focus on the cases (b) and (c), and add periodic cavity-modification on each optomechanical system to improve the degree of the quantum synchronization. The piezoelectric transducer can convert the electrical signal to mechanical vibration. We can use it to achieve the periodic modifications of cavity lengths [47], so as to realize the periodic modifications on the cavity frequencies and the detunings. In the following discussion, we choose the parameters that can be achieved experimentally [44] and we will explore whether the quantum synchronization of the system can be further improved by periodically modifying the cavities.

3.1. Modulation of cavity detunings with $K_1$ closed

For the situation that $K_1$ is closed and $K_2$ is open, the periodic modifications to the two cavities are applied at the same time ($\bar{\varepsilon} = \bar{\varepsilon} = \bar{\varepsilon}$, $\Omega_1 = \Omega_2 = \Omega$). As shown in figure 2, we plot mean value of quantum synchronization $\bar{S}_q(t)$ as a function of $\bar{\varepsilon}$ and $\Omega$ for a double cavity-mode modulation. The most parameter regions of $\bar{S}_q(t)$ is low; conversely, the regions where the cavity-modulation frequency $\Omega$ is an integral multiple of $\omega_{in}$ (such as 2 or 3) [35, 40] are so different with the increase of the cavity-modulation strength $\bar{\varepsilon}$. The reason is that energy can be transferred from external modulations to mechanical oscillators more simply and the peak positions may change from $\Omega = 2, 3$ to other integers depending, e.g., on the value of $\bar{\varepsilon}$ [35]. Besides, when $\Omega$ exceeds a critical value, the modulation effect may fail suddenly, i.e., $\bar{S}_q(t)$ become invariant [35]. It can be found that when $\Omega = 3, \bar{\varepsilon} = 0.9$, $\bar{S}_q(t)$ has the maximum value around 0.4, the degree of quantum synchronization has been greatly improved than previous works.

To further prove our conclusion, we examine in figure 3. As shown in figure 3(a), we fix $\Omega = 3, \bar{\varepsilon} = 0.9$ and show the solution of equation (4) for the mean values $Q(t)$ and $P(t)$ of the two mechanical oscillators’ position and momentum. The evolution tends indeed to an asymptotic periodic orbit and the two limit cycles tend to be consistent. From figures 3(b) and (c), we can see that the system reaches the stable state after a transient
The evolution of the mean values $Q_1(t)$ and $Q_2(t)$ tends to be coincident as shown in figure 3(b).

Meanwhile, the evolution of the mean values $P_1(t)$ and $P_2(t)$ also gradually tends to be coincident as shown in figure 3(c). From figure 3(d), we can see that the system reaches a steady state finally and the value of $S_{tc}(t)$ is around 0.4. To sum up, we found that the degree of quantum synchronization can be enhanced by introducing the periodic cavity-modifications and choosing appropriate parameters.

3.2. Modulation of cavity detunings with $K_2$ closed

Now we consider that switch $K_1$ is open and the switch $K_2$ is closed, the two coupled optomechanical systems interact mutually through a photon channel. The quantum synchronization of the systems without applying any modification is not very good. As discussed in the previous section 3.1, we apply the same periodic modifications to the two cavities ($\delta_1 = \delta_2 = \varepsilon_1, \Omega_1 = \Omega_2 = \Omega$).

As shown in figure 4, the most of the parameter regions are blue and the mean value of the quantum synchronization $S_{tc}(t)$ is low. However, one common feature of situation (b) and situation (c) is that optimal quantum synchronization occurs when $\Omega$ is an integral multiple of $\omega_{\text{mod}}$ (such as 2 or 3) \cite{35, 40} before a critical value. It can be found that when $\Omega = 3, \varepsilon = 0.9$, $S_{tc}(t)$ has its maximum value around 0.6, the quantum synchronization degree has greatly improved than previous work.

We examine in figure 5 to further prove our conclusion. As shown in figure 5(a), we set $\Omega = 3, \varepsilon = 0.9$ and show the evolution of the mean values $Q(t)$ and $P(t)$ which are position and momentum of the two oscillators, respectively. The evolution trends to an asymptotic periodic orbit (i.e. the two limit cycles tend to be consistent).
From figures 5(b) and (c), the system reaches the stable state after the transient evolution, because the evolution of $Q_1(t)$ and $Q_2(t)$ gradually tends to be coincident and the evolution of $P_1(t)$ and $P_2(t)$ does the same. From figure 5(d), we can see that the system reaches a steady state in the end and $Stc(0)$ rises toward the value around 0.6, which is obviously a better result. From the above discussions, we found that the degree of quantum synchronization can be enhanced by introducing the periodic cavity-modifications and choosing appropriate parameters.

3.3. Comparison of the two cases

According to the previous study, we apply the same periodic modulations to the cavities in two cases and the quantum synchronization has been greatly improved. As we known, it is important for a good modulation scheme to keep the synchronized system relatively stable with the increase of the bath’s mean temperature $T$ and the oscillators’ eigenfrequency difference $\Delta_m$. In other words, we want to measure the robustness of the modulation scheme we proposed. It is significant to examine how $Stc(t)$ reduces until negligible, because a large decrease of $Stc(t)$ may be resulted from a slight increase $T$ and $\Delta_m$.

We plot $Stc(t)$ versus the bath’s mean temperature $T$ in figure 6 and the oscillators’ eigenfrequency difference $\Delta_m$ in figure 7 for the optimal modulations in both cases. That is, each point represents the maximal value of $Stc(t)$, for a given value of $T$ and $\Delta_m$, obtained by choosing the optimal values of $\varepsilon$ and $\Omega$. As $T$ is gradually increased from $k_b/\hbar\omega_{m1}$ to $10 k_b/\hbar\omega_{m1}$ ($k_b$ is the Boltzmann constant) shown in figure 6(a), the two curves show a gradual downward trend and the degree of decline is different. It is obvious that the trend of decline in the
second case is larger. Then we continue to increase $T$ from $10k_0/\hbar\omega_{m1}$ to $100k_0/\hbar\omega_{m1}$ as shown in figure 6(b), the trend of decline in the second case is still larger. It is clear that the optimal modulation in the first case results in a better quantum synchronization than that in the second case with the increase of $T$.

As shown in figure 7, we check the robustness of quantum synchronization against the oscillators’ eigenfrequency difference $\Delta_m$. It is worth to notice that $\Delta_m$ is chosen to 0.005 in the previous article ($\omega_{m1} = 1$, $\omega_{m2} = 1.005$, $\Delta_m = \omega_{m2} - \omega_{m1} = 0.005$ in figure 2). Now we compare the system stability in the two cases by changing $\Delta_m$ and find that the difference of two lines is distinct.

Though the downtrend of $\bar{S}_c(t)$ in both cases is small when $\Delta_m$ is increased from 0 to 0.01. However, the trend of decline in the second case is larger when we increase $\bar{S}_c(t)$ from 0.01 to 0.025. Especially, when $\Delta_m$ is 0.025, $\bar{S}_c(t)$ is about 0.068 in the second case and it is almost impossible for the system to achieve synchronization at that time. Conversely, $\bar{S}_c(t)$ declines slightly in the first case. Only when $\Delta_m$ is greater than 0.025 or more, there will be a large decline. Therefore, It is obvious that the optimal modulation in the first case results in a better quantum synchronization than that in the second case with the increase of $\Delta_m$.

4. Conclusion and discussion

In summary, we have studied a coupled optomechanical system in which the couplings are controlled by two switches and analyzed the different scheme of the switches’ setups. The degree of quantum synchronization in the system without any modification is found to be bad. After detailed analysis and comparison, we find that appropriate modulations on cavity detunings can enhance the quantum synchronization in our system. Besides, two types of switches setups with periodic modulation are compared. An examination of the robustness of $\bar{S}_c(t)$ against $T$ and $\Delta_m$ shows that the first case ($K_1$ off and $K_2$ on) is more appealing in achieving a preferable quantum synchronization behavior than the second case ($K_1$ on and $K_2$ off). Compare to the former studies [35] (as $K_1$ is closed and $K_2$ is open) and [3] (as $K_1$ is open and $K_2$ is closed), the periodically modulating cavity detunings greatly enhance the quantum synchronization and are robust against thermal fluctuations and the eigenfrequency difference. All in all, we believe that our scheme is effective and can be used to improve the degree of quantum synchronization under different conditions.

Acknowledgments

This work is supported by National Natural Science Foundation of China (NSFC) (Grants No. 11534002, No. 61475033, and No. 11405088), and the Plan for Scientific and Technological 739 Development of Jilin Province (Grant No. 20160520173JH).

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References

[1] Leone M J et al 2015 Phys. Rev. E 91 032813
[2] Tang G et al 2011 Phys. Rev. E 84 046207
[3] Vaidyanathan S 2015 International Journal of ChemTech Research 6 795–803
[4] Romashko D N et al 1998 Proc. Natl. Acad. Sci. USA 95 1618–23
[5] Marie A et al 2013 Phys. Rev. Lett. 111 103605
[6] Ludwig M and Marquardt F 2013 Phys. Rev. Lett. 111 073603
[7] Wei T et al 2016 New J. Phys. 18 013043
[8] Ameri V et al 2015 Phys. Rev. A 91 012301
[9] Zhirov O V and Shepelyansky D L 2009 Phys. Rev. B 80 014519
[10] Xu M H and Holland M J 2015 Phys. Rev. Lett. 114 103601
[11] Hush M R et al 2015 Phys. Rev. A 91 061401 R
[12] Xu M H et al 2014 Phys. Rev. Lett. 113 154101
[13] Walter S et al 2014 Phys. Rev. Lett. 112 094102
[14] Lee T E et al 2014 Phys. Rev. E 89 022913
[15] Lee T E and Sadeghpour H R 2013 Phys. Rev. Lett. 111 234101
[16] Walter S et al 2015 Ann. Phys. (Leipzig) 527 131–8
[17] Wei T et al 2017 Phys. Rev. A 95 041802
[18] Samoylova M et al 2015 Opt. Express 23 014823
[19] Vinokur V M et al 2008 Nature (London) 452 613–5
[20] Hriscu A M and Nazarov Y V 2013 Phys. Rev. Lett. 110 097002
[21] Bagheri M et al 2013 Phys. Rev. Lett. 111 213902
[22] Matheny M H et al 2014 Phys. Rev. Lett. 112 014101
[23] Zhang M et al 2015 Phys. Rev. Lett. 115 163902
[24] Zhang M et al 2012 Phys. Rev. Lett. 109 233906
[25] Shlomi K et al 2015 Phys. Rev. E 91 032910
[26] Vitali D et al 2007 Phys. Rev. Lett. 98 030405
[27] Vitali D et al 2007 J. Phys. A 40 053854–68
[28] Yang X H et al 2017 Phys. Rev. A 95 052303
[29] Wang T et al 2016 Commun. Theor. Phys. 65 596–600
[30] Marie A and Eisert J 2009 Phys. Rev. Lett. 103 213603
[31] Choi S H and Ha S Y 2014 J. Phys. A 47 353104
[32] Bellomo B et al 2017 Phys. Rev. A 95 043807
[33] Bernani F et al 2017 Phys. Rev. A 96 023805
[34] Miliutello B et al 2017 Phys. Rev. A 96 023862
[35] Li W L et al 2015 J. Phys. B 48 035503 2015
[36] Li W L et al 2017 Phys. Rev. E 95 022204
[37] Li W L et al 2016 Phys. Rev. E 93 062221
[38] Yi X X et al 2009 Phys. Rev. A 80 052316
[39] Hou S C et al 2012 Phys. Rev. A 86 022321
[40] Farace A and Giovannetti V 2012 Phys. Rev. A 86 013820
[41] Woolley M J et al 2008 Phys. Rev. A 78 062303
[42] Marie A and Eisert J 2012 New J. Phys. 14 075014
[43] Chen R X et al 2014 Phys. Rev. A 89 023843
[44] Du L et al 2017 Sci. Rep. 7 15834
[45] Ying L et al 2014 Phys. Rev. A 90 033810
[46] Joshi C et al 2012 Phys. Rev. A 85 033805
[47] Liao J Q et al 2015 Phys. Rev. A 92 013822
[48] Wang Y D and Clerk A A 2013 Phys. Rev. Lett. 110 253601
[49] Genes C et al 2009 Adv. At. Mol. Opt. Phys. 57 33–86
[50] Giovannetti V and Vitalii D 2001 Phys. Rev. A 63 023812
[51] Liu Y C et al 2014 Phys. Rev. A 89 053821
[52] Xu X W and Li Y 2015 Phys. Rev. A 91 053854
[53] Wang G L et al 2014 Phys. Rev. Lett. 112 110406
[54] Larson J and Horsdal M 2011 Phys. Rev. A 84 021804
[55] Jesus E X D and Kaufman C 1987 Phys. Rev. A 35 5288