Incoherent control of two-photon induced optical measurements in open quantum systems: Quantum heat engine perspective

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Introduction

Recently, the authors developed an incoherent control [1] method of optical signals that views the pump-probe measurements as a QHE, which transfers energy from the pump pulse to the probe pulse, treating the dissipation to the environment explicitly, while computing the work performed by the system via the detected probe photons.

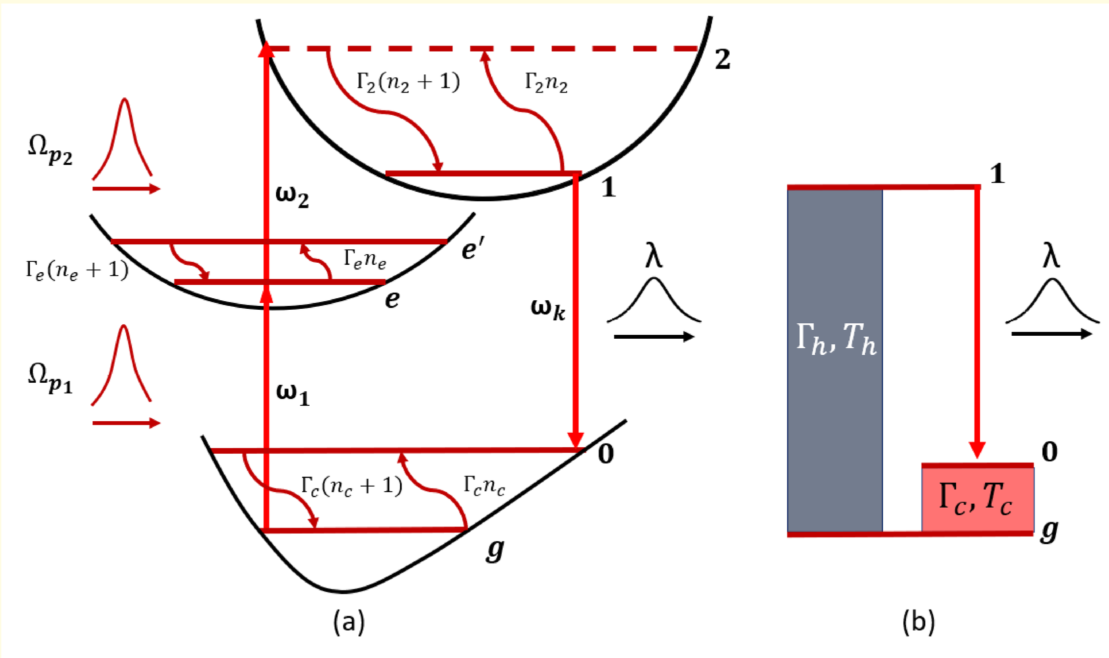

Figure 1: (a) Schematic for the three-level molecule undergoing two-photon pump-probe measurements. The pump field resonant with transition $g-2$ excites a vibrational wave packet in the higher vibrational state 2 via the intermediate levels e and e', which relaxes to the lower energy vibrational state 1. The probe field then stimulates the emission from state 1 to the excited vibrational level 0 in the ground electronic state. Finally, vibrational relaxation brings the system back to its ground state g. (b) Equivalent three-level QHE with transitions between energy levels $g-1$ and $g-0$ driven by hot (at temperature T_h) and cold (at T_c) heat baths. The single-mode stimulated emission representing the work done by the QHE occurs at the $1-0$ transition with the Rabi frequency λ
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By presenting a consistent technique of maximization of power and efficiency at maximum power for the two-photon pumped QHE using incoherent control, one can manipulate the two-photon induced fluorescence (TPIF) and pump-probe signals due to an additional control parameter (entanglement time), which does not exist classically.

Abstract

We present a consistent optimization procedure for the optical measurements in open quantum systems using recently developed incoherent control protocol. Assigning an effective hot bath for the two-entangled-photon pump we recast the transmission of classical probe as a work in a quantum heat engine framework. We demonstrate that maximum work in such a heat engine can exceed that for the classical two-photon and one-photon pumps, while efficiency at maximum power can be attributed to conventional boundaries obtained for three-level maser heat engine. Our results pave the way for incoherent control and optimization of optical measurements in open quantum systems that involve two-photon processes with quantum light.

Effective bath & efficiency

We first introduce an effective heat bath. To that end, we assume that the probe field is much stronger than the coupling to the phonon bath that governs the $2-1$ transition, which itself is stronger than that of the bath driving $0-g$ transition: $\lambda >> \Gamma_2 n_2 >> \Gamma_c n_c$. The solution we obtain the population of level 1

$$\begin{aligned}
\rho_{11}^{c}(t) &= \frac{16\,\delta^2\,\tilde{\delta}^2\,\Omega_p^4\,(1-e^{-\Gamma_2(2n_2+1)})}{(2n_2+1)(\delta^2+4\sigma_p^2)^2(\tilde{\delta}^2+4\sigma_p^2+)^2},\\
\rho_{11}^{th}(t) &= \mathcal{N}_{th} n_h (1-e^{\Gamma_h(2n_h+1)t}), \qquad (1)
\end{aligned}$$

where $\tilde{\delta} = \delta + 2\omega_{2e'} - 2\omega_{e'g}$. In order to match the solutions of the coherent excited populations in Eq. (1) with that of thermal bath in Eq. (1), the corresponding n_h and Γ_h must satisfy

$$\begin{aligned}
n_h &= \frac{16\,\Omega_p^4\,(n_2+1)\delta^4}{\tilde{n}_2(\delta^2+4\sigma_p^2)^4 - 32\,\Omega_p^4\,(n_2+1)\,\delta^4}\\
\Gamma_h &= \Gamma_2 \frac{\tilde{n}_2(\delta^2+4\sigma_p^2) - 32\,\sigma_p^4(n_2+1)\delta^4}{(\delta^2+4\,\sigma_p^2)^4}, \qquad (2)
\end{aligned}$$

where $\tilde{n}_2 = 2n_2+1$. We introduce an effective temperature of the hot bath $T_h = (\Omega_p\,\Gamma_2^2\,/2\,\delta)^{1/2}$ and the dimensionless temperature scale: $\tau = T_c/T_h$. The pump energy scale $c_p = \omega_p/\omega_c$, the coupling scale: $\lambda' = \lambda(\Gamma_2 T_c)^{-1/2}$ and the pump pulse width scale: $\sigma_p' = \sigma_p^e\,\Gamma_2/\delta T_c$ and by introducing the detuning $\delta = \omega_{2e} - \omega_{2e'}$ and assuming the pump is tuned midway between e and e' states $\omega_0 = \frac{1}{2}(\omega_{2e'} + \omega_{2e})$
We assume the weak dissipation regime i.e., $\omega_c >> \Gamma_c$ which yields

$$\begin{aligned}
\eta_{CW}^{*} &= 1 - \frac{1}{c_p + \frac{\alpha^2 uv}{\tau^8\sigma_p'^8\left(\tau^8(c_p-1)\lambda'\sigma_p'^8+\alpha u\lambda'\right)}}\\
\eta_{QW}^{*} &= 1 - \frac{1}{c_p + \frac{u\,v\,\alpha^2\,\theta^2}{\tau^4\lambda'\sigma_p'^4\left(\alpha\,u\,\theta+(c_p-1)\tau^4\sigma_p'^4\right)}} \qquad (3)
\end{aligned}$$

where $\theta = sinc^2[T\,(\omega_{2e'} - \omega_{ge'})\,/2]$. The effective bandwidth for the two-classical and two-entangled photon pump vs η_C is given in Eq. 3. Furthermore, the efficiency corresponding to the maximum output power for the quantum light is more robust than that for the classical light for the moderate range of τ as discussed in arXiv:2203.04268 (accepted in PRR). the particular boundary is reached at different pump parameters. For instance, a CA limit is obtained for the single photon pump at $c_p \simeq 2/\sqrt{\tau}$ and for the two photons $c_p \simeq 1/\sqrt{\tau}$ and its corresponding Rabi frequency is $\Omega_p^{CA} \simeq (4\omega_p/\omega_c)^4 T_c^2 \delta/\Gamma_2^2$. The factor of two, which appears in the other bounds as well, originates from the quadratic scaling of the photon absorption probability with the input intensity for the classical light.

Power Optimization

Strong coupling regime (QHE) The ratio of maximum power corresponding classical and entangled two - photon pump is given by

$$\frac{P_Q^{max}}{P_C^{max}} = \tau^{-4}\sigma_p'^{-4} sinc^{-2}\Big[\frac{T(\omega_{2e'} - \omega_{ge'})}{2}\Big] \qquad (4)$$

which gives $P_Q^{max} > P_C^{max}$ for $sinc^2[T(\omega_{2e'} - \omega_{ge'})/2] \simeq 1$ and $\sigma_p'\tau < 1$. The above analysis clearly indicates the relation between the effective bath temperature, the entanglement time and the spectral bandwidth of the optical fields as well as the system energy scale and its effect on the optical measurements with the entangled light in the open quantum systems. For instance in the limit of short entanglement time we can achieve quantum enhancement even in highly anharmonic system as long as $|\omega_{2e'} - \omega_{e'g}| << 1/T$.
Similarly, for the long entanglement time the quantum enhancement can be reached for nearly harmonic system ($\omega_{2e'} \simeq \omega_{e'g}$). In the same time inequality $\sigma_p'\tau < 1$ yields an additional requirement for the pumping source such that $\Omega_p > 4\delta(\sigma_p^e)^2/\Delta^2$.

Spectroscopic regime: We now focus on the pump - probe spectroscopic signal derived by perturbative approach in light - matter interaction. The ratio of maximum power for the corresponding classical and entangled two - photon pump

$$\frac{\mathcal{P}_Q^{max}}{\mathcal{P}_C^{max}} = \tau^4\sigma_p'^4 sinc^2\Big[\frac{T\,(\omega_{2e'} - \omega_{ge'})}{2}\Big]. \qquad (5)$$

For the short entanglement time $sinc^2\big[\frac{T(\omega_{2e'}-\omega_{ge'})}{2}\big] \simeq 1$ and in the limit of $\sigma_p'\tau > 1$ we obtain $\mathcal{P}_Q^{max} > \mathcal{P}_C^{max}$. We therefore identified the parameter regime where maximum power for the entangled two-photon pump is enhanced compared to the classical case using perturbative regime. In comparison to QHE (nonperturbative) regime the power increase due to the entanglement in spectroscopic (perturbative) regime occurs when the bath temperature ratio is $\tau > 1/\sigma_p'$, whereas in the former case $\tau < 1/\sigma_p'$, which agrees with strong pumping (nonperturbative) vs weak pump (perturbative) limit taken in these two cases.
we demonstrated numerically in [arXiv:2203.04268] (accepted in Physical Rev. Research), that the maximum power for the quantum light is much larger than that for the classical light within for the moderate range of $\tau < 1$.

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Conclusion

- In this proposed model we analytically explored the characteristics of two-photon absorptions for classical and entangled pair of photons and their dependence on additional degrees of freedom, due to which we get the maximum work, in both the weak and strong intensity approximations.
- In the present analysis the two-photon absorption in the open quantum system regime benefits from additional control parameters using an incoherent control scheme by mimicking QHEs.
- Our results can be further extended to Raman, hyper-Raman, and other techniques that require additional control over illumination intensity and pump light statistics.

References

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2. K. E. Dorfman, D. Xu, and J. Cao, Phys. Rev. E 97, 042120 (2018).