Optical simulation of a quantum thermal machine

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We introduce both a theoretical and an experimental scheme for simulating a quantum thermal engine through an all-optical approach, with the behavior of the working substance and the thermal reservoirs implemented via internal degrees of freedom of a single-photon. By using polarization and propagation path, we encode two quantum bits and then implement the thermodynamical steps of an Otto cycle. To illustrate the feasibility of our proposal, we experimentally realize such simulation through an intense laser beam, evaluating heat and work at each individual step of the thermodynamical cycle. In addition, from the analysis of the entropy production during the entire cycle, we can study the amount of quantum friction produced in the Otto cycle as a function of the difference of temperature between hot and cold reservoirs. Our investigation constitutes, therefore, an all-optical-based thermal machine and opens perspectives for other optical simulations in quantum thermodynamics.

I. INTRODUCTION

The idealization of microscopic quantum systems allowing for extraction of work and heat is at the heart of quantum thermal engines (QTEs), quantum refrigerators [1–3], and quantum batteries [4, 5]. In analogy with its classical counterpart, a QTE has a quantum system as its working substance, which interacts with thermal reservoirs at different temperatures βc and βh. However, due the quantum nature of the working substance, one expect that the performance of a QTE may go beyond that of a classical engine [6, 7]. Concrete proposals of QTEs have been studied in recent years from different approaches [8–14]. Indeed, experimental verifications of the performance of a QTE have recently been achieved, e.g., nuclear spin systems manipulated through nuclear magnetic resonance (NMR) [15] and nitrogen-vacancy centers in diamond [16]. In general, a major difficulty for implementing QTEs in real physical systems is the high controllability required so that robustness against of decoherence is achieved. Therefore, there is great interest in designing QTEs from architectures that offer efficient control of reservoirs.

In order to simulate controllable reservoirs, we have to consider the effect of quantum channels acting on quantum information [17]. In this context, it is fundamental in our approach to take into account the optical implementation of relevant quantum channels, as amplitude damping, phase-damping, bit flip channels, among others performed by using single photons [18]. On the other hand, degrees of freedom of an intense laser beam have been widely used to simulate single-photon experiments and the results show that such procedure consists in a relevant test-bed for several quantum properties in a rather simple way [19]. Indeed, it can be shown that such systems provide realizations of quantum inequalities violations [20–22], quantum key distribution [23], teleportation [24] and quantum logical gates [25, 26]. As a further implementation of interest here, it is important to highlight the experimental simulation of open quantum systems to investigate environment-induced entanglement [27]. In this paper, we propose an all-optical-based scheme, which allows us to simulate the performance of a thermal machine in quantum mechanics and perform an experimental simulation by using degrees of freedom of an intense laser beam. We theoretically show how we can construct a quantum machine by using the phase damping channel as a thermal reservoir. We then simulate the Otto cycle for polarization of a single-photon via a linear optical circuit.

II. THE THERMAL MACHINE

Let us begin by the definition of heat and work in quantum mechanics. In general, heat and work are not quantum observables [28]. However, for the processes of interest here, either heat or work will be vanishing. In this situation, convenient expressions can be derived from the first law of thermodynamics. Indeed, by considering the internal energy $U(t)$ of a quantum system described by a density operator $\rho(t)$ at instant $t$ as $U(t) = \text{Tr} \{H(t)\rho(t)\}$, with $H(t)$ denoting the Hamiltonian of the system, it is possible to define work $\delta W(t)$ and heat $\delta Q(t)$ for infinitesimal processes as

$$\delta W(t) = \text{Tr} \{H(t)\rho(t)\} \, dt, \quad (1)$$

$$\delta Q(t) = \text{Tr} \{H(t)\dot{\rho}(t)\} \, dt. \quad (2)$$

Notice that $\delta W(t) > 0 \ (\delta W(t) < 0)$ implies that work is being performed on (by) the system, so that its internal energy is increasing (decreasing). Similarly, when $\delta Q(t) > 0 \ (\delta Q(t) < 0)$ we say that heat is being injected in (extracted from) the system.

The steps of our thermal machine is as follows. **Gap expansion step** – Initially a quantum bit (qubit) is prepared in a thermal state of the reference Hamiltonian $H_e(0) = \omega_{\text{in}} \sigma_y$, at inverse temperature $\beta_c$. Thus, the system undergoes a unitary dynamics driven by the Hamiltonian $H_e(t) = \hbar \{\omega_{\text{in}} f(t) + \omega_{\text{fin}} g(t)\} \sigma_y$, with functions $\{g, f\} : t \in \mathbb{R} \rightarrow$
$g, f \in \mathbb{R}$ satisfying $g(0) = f(\tau) = 1$ and $g(\tau) = f(0) = 0$ and $|\omega_{\text{ini}}| < |\omega_{\text{fin}}|$. In this step, an amount of work is performed on or by system. **Thermalization with hot reservoir** – At this stage, the system is coupled to a thermal reservoir at inverse temperature $\beta_n$, thermalizing with it. Therefore, the final state at this step is a thermal state of the Hamiltonian $H_c(\tau)$ at inverse temperature $\beta_c$. In this step, the system exchange heat with the reservoir, but no work is performed. **Gap compression step** – Now, we switch off the interaction between the system and the reservoir. Thus, we drive the system by a time-dependent Hamiltonian $H_c(t) = \hbar \left[\omega_{\text{ini}}f(t) + \omega_{\text{ini}}g(t) \right] |\sigma_y\rangle$. In this step, only work is performed on or by the system. **Thermalization with cold reservoir** – To end, the system is coupled to the cold reservoir, in which the final state is the thermal state of the Hamiltonian $H_c(\tau)$ at inverse temperature $\beta_c$. No work is performed, but heat is exchanged between the system and the cold reservoir.

From Eqs. (1) and (2) we can compute heat and work for each step of this Otto cycle (shown in Fig. 1) as

$$W_{A \rightarrow B} = -\hbar (\omega_{\text{ini}} - \omega_{\text{fin}}) \tanh(\hbar \omega_{\text{ini}} \beta_n),$$

$$Q_{B \rightarrow C} = \hbar \omega_{\text{ini}} \left[ \tanh(\hbar \omega_{\text{ini}} \beta_n) - \tanh(\hbar \omega_{\text{ini}} \beta_n) \right],$$

$$W_{C \rightarrow D} = \hbar (\omega_{\text{ini}} - \omega_{\text{fin}}) \tanh(\hbar \omega_{\text{ini}} \beta_n),$$

$$Q_{D \rightarrow A} = -\hbar \omega_{\text{fin}} \left[ \tanh(\hbar \omega_{\text{fin}} \beta_c) - \tanh(\hbar \omega_{\text{fin}} \beta_c) \right],$$

where we can derive the condition between $\beta_c$ and $\beta_n$ in order to get $Q_{D \rightarrow A} < 0$ as $\omega_{\text{fin}} \beta_c > \omega_{\text{ini}} \beta_n$. Such condition establishes the relation between the parameters of the reservoir and Hamiltonian as $T_h/T_c > \omega_{\text{fin}}/\omega_{\text{ini}}$.

### A. Photon phase-damping channel as a thermal reservoir

We can simulate the required reservoirs for implementing a quantum machine by using a dephasing quantum channel for a single-photon. To see this, we first need to realize that our system is initially prepared in a thermal state of $H_{\text{ini}}$ at inverse temperature $\beta_n$, which reads

$$\rho_{\text{ini}}^{th} = \frac{1}{2} \left[ 1 + \tanh(\hbar \omega_{\text{ini}} \beta_n) |\sigma_y\rangle \langle \sigma_y| \right].$$

Thus, due to the contact of our system with a thermal reservoir at inverse temperature $\beta_n$, under action of the Hamiltonian $H_{\text{fin}}$, the state after thermalization will be

$$\rho_{\text{fin}}^{th} = \frac{1}{2} \left[ 1 + \tanh(\hbar \omega_{\text{ini}} \beta_n) |\sigma_y\rangle \langle \sigma_y| \right].$$

Thus, the reservoir just changes the off-diagonal elements of the initial state, from $\tanh(\hbar \omega_{\text{ini}} \beta_n)$ to $\tanh(\hbar \omega_{\text{ini}} \beta_n)$. On the other hand, given a density matrix $\rho$ with elements $\rho_{\text{ini}}$, we know that a phase-damping channel acts over the elements $\rho_{01} = \rho_{10} e^{-\tau \gamma}$, $\rho_{10} = \rho_{01} e^{-\tau \gamma}$, respectively, where $\gamma$ is the dephasing rate and $\tau$ is the time interval of interaction of our system with the decohering reservoir. To conclude, by applying this map to the state $\rho_{\text{ini}}$, we have $\tanh(\hbar \omega_{\text{ini}} \beta_n) \rightarrow e^{-\tau \gamma} \tanh(\hbar \omega_{\text{ini}} \beta_n)$, so that we can adjust the parameters $\gamma \tau$ to get the parameter $\beta_n$ from

$$\hbar \omega_{\text{ini}} \beta_n = \arctanh \left[ e^{-\tau \gamma} \tanh(\hbar \omega_{\text{ini}} \beta_n) \right].$$

Thus, one can use the phase-damping channel to simulate the thermal reservoir in a heat engine, where we set the parameter $\gamma \tau$ to encode the hot reservoir temperature.

In several schemes of QTEs [8–14], both steps of compression and expansion are performed by slow (adiabatic) unitary evolution, so that an amount of work is performed on or by the system and no heat is exchanged. However, since any unitary dynamics suppresses the heat exchange (closed system), we can implement a fast evolution in this step [29]. In single-photon experiments we can simulate the dynamics of a quantum system through unitary operators, thus the expansion and compression steps are implemented by unitary $U_c(\tau)$ and $U_c(\tau)$, respectively, where $\tau$ is the total compression/expansion time interval (adopted to be the same in both steps). By writing the expansion/compression Hamiltonian as $H_{\text{ini}}(t) = \hbar \omega_{\text{ini}}(t) |\sigma_y\rangle \langle \sigma_y|$, the unitary evolution operator is given $U_c(\tau) = e^{-i \omega_{\text{ini}}(t) \tau}$, where we denote $\omega_{\text{ini}} = (1/\tau) \int_{\tau} \omega_{\text{ini}}(t) dt$. During this evolution, an amount of work is calculated from (3) and (5), respectively.

### III. EXPERIMENTAL IMPLEMENTATION

In this section we discuss about how we can encode the quantum thermal cycle discussed above in our particular system, where an general schematic representation is shown in Fig. 1. The working substance in our system, as well as any auxiliary system, is encoded in the degree of freedom of a laser beam. The qubit associated with the machine, in which we will extract/introduce heat and work, is the two independent photon polarization states $|V\rangle$ (vertical) and $|H\rangle$ (horizontal).

#### A. Phase-damping channel with linear optical circuits

The experimental implementation of the phase damping (PD) channels that simulates the thermal reservoirs has been performed by using linear optical circuits. In our experiment, instead of a single-photon source, we used an intense laser beam that can be described by a coherent state with a macroscopic photon number. This approach has been successfully explored in literature in different scenarios [23–27]. For this reason, we will present the experiment by using Dirac notation for polarization states once the discussion for single-photon states is straightforward. We encoded the qubit in the polarization degree of freedom and the environment in the propagation direction (path). For the polarization states, we have a two-level system, where we can associated the horizontal polarization as a ground state ($|H\rangle_S \equiv |0\rangle_S$) and the vertical polarization as an excited state ($|H\rangle_S \equiv |0\rangle_S$). In case of the propagation direction, we encoded the path also as a two-level system, with orthogonal directions, $\hat{e}_0$ and $\hat{e}_1$, representing the reservoir ground ($|0\rangle_R$) and excited state ($|0\rangle_R$), respectively.

The scheme for the PD channel is shown in Fig. 1 (PD1, red square in the circuit). To describe the channel action on the polarization states, let us consider, without loss of generality, an incoming laser beam described by a right-circular polarized

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state
\[ |\psi_{RL}⟩ = \frac{1}{\sqrt{2}} (|H⟩ - i|V⟩) , \] (10)
which will interact with the reservoir. Therefore, as the state \(|\psi_{RL}\rangle\) arrives at the channel, the polarization beam splitter PBS1 transmits (reflects) the horizontal (vertical) polarization state. In this way, the H-polarization component (H) goes to the half-wave plate HWP4@θ₂ (θ₂ = 0°), where no change occurs in the polarization component (H) of transmitted arm. On the other hand, for the reflected arm, the V-polarization component passes through HWP3@θ₁, implementing the transformation
\[ |V⟩_S → \sin(2θ₁)|H⟩_S + \cos(2θ₁)|V⟩_S \] . (11)
Moreover, in this reflected arm, we introduced a piezoelectric ceramic (PZT) placed in the mirror for adjusting the difference of phase (Δφ) between the two arms. In this way, by adjusting Δφ = 0, we have the state of polarization of the transmitted arm going out to PBS2 in the path |0⟩_R. For the reflected arm, after the transformation implemented by HWP3, the H-polarization component of (11) leaves PBS2 in the path |1⟩_R and the V-polarization component of (11) is reflected to the path |0⟩_R. The last stage of the channel is implemented by another half-wave plate (HWP5@45°) introduced in the path |1⟩_R. This device turns \(|H⟩_S → |V⟩_S\). Thereby, the transformations implemented by this channel in the initial state \(|\psi_{RL}\rangle\) can be written as the map (by using the notation \(|x⟩|y⟩ = |x⟩_S |y⟩_R\))
\[ \begin{pmatrix} (|H⟩ - i|V⟩) |0⟩ \rightarrow |H⟩ |0⟩ - i(\cos 2θ₂ |V⟩ |0⟩ + \sin 2θ₂ |V⟩ |1⟩) \end{pmatrix} , \]
up to a normalization factor \(1/\sqrt{2}\) on both sides. If we consider the definition of the PD channel in terms of its Kraus operators [17], we obtain the map
\[ \begin{pmatrix} (|0⟩ - i|1⟩) |0⟩ \rightarrow |0⟩ |0⟩ - i[1 - p(t)]^{1/2} |1⟩ |0⟩ - ip^{1/2}(t) |1⟩ |1⟩ \end{pmatrix} , \] (13)
where \(p(t) = 1 - e^{-\gamma t}\), being γ the decay rate. By comparing Eqs. (12) and (13), we get
\[ \cos^2(2θ₁) = 1 - p(t) . \] (14)
Therefore, HWP3 simulates the time evolution during the PD channel. For the initial condition \(p(t = 0) = 0\), where the system does not interact with the reservoir, we have \(θ₁ = 0°\). In this case, HWP3 does not implement any change in the polarization state and, as expected, nothing happens with the initial state. Consequently, coherence does not decrease. On the other hand, for the asymptotic behavior, \(p(t → ∞) = 1\), HWP3 implements the maximum rotation in the polarization state and the state completely loses its coherence.

**B. Otto cycle with linear optical circuits**

In order to realize the Otto cycle, we start with the state preparation. As shown in Fig 1, a vertically polarized DPSS laser (1.5 mW power, λ = 532 nm) pass through a quarter-wave plate QWP1@−45° to produce a right-circular polarization that is the analogue of the initial state \(|\psi_{RL}\rangle\). The laser beam passes into a spatial filter SF in order to improve the fundamental transverse mode quality. The initial state is verified by performing state tomography in the polarization of the laser beam at point \(T_A\). Polarization tomography can be performed by following Ref. [30], with its associated apparatus shown at the end of the circuit. The adiabatic expansion \(AB\) is performed by the unitary evolution operator \(U_A(Ωt)\), where the gap expansion given by \(\omega(t) = \omega_0(1 - t/τ) + \omega_0(t/τ)\) is realized by two half-wave plates HWP1 and HWP2, with their fast axes performing an angle of θ between them. By using the Jones matrices \(S(α)\) for polarization manipulation [31], it is possible to show that the dimensionless quantity \(Ωt\) can be associated with the angle θ between HWP1 and HWP2 as \(Ωt = θ\). In our experiment, we consider \(Ωt = θ = π/2\). Note that, from the initial state, the circular polarization remains unchanged up to a global phase, which corresponds to the evolution of the eigenstates of the Hamiltonian. At point \(T_B\), we perform the tomography of the evolved state. Following the cycle, the step \(BC\) corresponds to the hot reservoir. This part is simulated by PD1. Note that the amount of heat \(Q_{B→C}\) is related to the angle \(θ_τ\), as described above to the evolution in the PD channel. A new tomography tracing out the environment is performed in \(T_C\) in the two outputs of PD1 exactly as depicted in the dashed box at end of the circuit. The step \(CD\) corresponds to the adiabatic compression and is also realized by two half-wave plates. Note that each output of PD1 passes through a couple of wave plates (HWP3, HWP5) at the same angles of the couple HWP1, HWP2 of step \(AB\). This set of angle simulates the compression to the same initial volume, since the gap compression is considered as \(\omega(t) = ω_0(t/τ) + ω_0(1 - t/τ)\). A new tomography of the state is performed at \(T_D\). In order to complete the cycle, at step \(DA\), it is necessary to return to the initial state. Therefore, the action of the PD channel should be undone. We can perform this operation by the circuit I-PD (inverted PD Channel).
HWP₁₀ at 45° undoes the action of HWP₅. In the interferometer, HWP₁ at θ₁ = −θ₂ and HWP₂ at θ₁/₂ = 0 undo the action of HWP₃ at +θ₅. PBS regroups the arms [0] and [1], with the relative phase controlled by PZT₂ in order to obtain the initial state (circular polarization). A tomography is performed at point $Tₐ$.

### IV. RESULTS AND DISCUSSION

From Eqs. (3–6) we compute $Q$ and work $W$ from the internal energy variation $\Delta U$ at each step of the Otto cycle. By using the definition of internal energy as $U = \text{Tr}(H\rho)$, for some reference Hamiltonian $H$, we evaluate $U$ from the experimental density matrix after each thermodynamical process, which is obtained by performing quantum state tomography. Then, we have

$$ W = \text{Tr} \{ \rho(\tau) H(\tau) - \rho(0) H(0) \},$$

$$ Q = \text{Tr} \{ H(\tau) [\rho(\tau_0) - \rho(\tau)] \}. $$

In our experimental implementation, we start from the thermal state of the Hamiltonian $H_c(0) = \hbar \omega_0 \sigma_y$, with $\text{tanh} (\hbar \omega_0 \beta_c) \approx 1$ (corresponding to $\hbar \omega_0 \beta_c \approx 3$). In this initial state is $\rho_{\text{in}} \approx |\Phi_{\text{RL}}\rangle \langle \Phi_{\text{RL}}|$. The results are presented in Fig. 2. In Fig 2a, we show the internal energy variation $\Delta U / \hbar \omega_0$ as a function of $\hbar \omega_0 \beta_c$ for each step of the cycle for seven different values of the inverse hot temperature $\beta_h$. In this plot, work and heat have experimentally been obtained by Eqs. (15) and (16), respectively. For a closed cycle, $\Delta U$ must be zero, which can be observed by summing up $W$ and $Q$ for all the curves at a fixed value of $\beta_c$. Fig. 2b shows the extracted work, quantified from difference $[Q_{\text{h-c}}] - [Q_{\text{D-A}}]$, due to the coupling of the system with thermal baths at different inverse temperatures $\beta_c$ and $\beta_h$. As expected, the extracted work decreases as the inverse hot temperature $\beta_h$ increases. In addition, note that the energy balance $\Delta U_c$, is kept close to zero, as theoretically predicted. To study the entropy production, we consider the relative entropy during expansion/compression processes in a non-equilibrium regime, which is given by [32]

$$ \langle \Sigma \rangle_{\text{c/e}} = \mathcal{D} \left[ U_{\text{c/e}}(\tau) \rho_{\text{th}}^{\text{cold/hot}} - U_{\text{c/e}}(\tau) \rho_{\text{th}}^{\text{cold/hot}} \right], $$

where $\mathcal{D}[A|B] = \text{Tr} \{ A \log A - \text{Tr} \{ A \log B \} \}$, with $U_{\text{c/e}}(\tau)$ being the unitary evolution operator associated with the expansion/compression step and $\rho_{\text{th}}^{\text{cold/hot}}$ being the thermal state of the system associated with the cold/hot reservoir. As originally proposed, $\langle \Sigma \rangle_{\text{c/e}}$ quantifies the distance from the thermal equilibrium after an irreversible process in quantum thermodynamics. For a recent experimental implementation in NMR, see Ref. [33].

From thermodynamical cycles, the entropy production accounts for the dissipated energy during the expansion/compression steps, which may quantify quantum friction during the quantum evolution [34, 35]. The results are shown in Fig. 2c. Observe that the individual amounts of entropy production $\langle \Sigma \rangle_{\text{c}}$ and $\langle \Sigma \rangle_{\text{e}}$ associated with expansion and compression steps, respectively, are nonvanishing, which implies in a nonvanishing total entropy production $\langle \Sigma \rangle_c$ for thermal baths with distinct inverse temperatures $\beta_c$ and $\beta_h$. Notice that, as theoretically predicted, $\langle \Sigma \rangle_c$ vanishes as $\beta_h$ gets nearer $\beta_c$.

### V. CONCLUSIONS

In summary, we introduced a map from a single-qubit thermal machine into a single-photon setup. The feasibility of this proposal has been experimentally tested by an all-optical experiment realized through an intense laser beam. By using the polarization degree of freedom of the laser beam, we encoded a qubit as the working substance, while the two thermal baths are simulated by an auxiliary degree of freedom, which was the propagation path in our experiment. We have then shown how different thermal baths can be implemented with optical devices, with the difference of temperatures controllable through a dimensionless parameter associated with a combination of half-wave plates. Agreement between experimental and theoretical results is remarkable, with errors within...
a 5% range. It is worth emphasizing that we are proposing a simulation of thermal machine with all-optical devices. However, our investigation opens perspectives for implementations of other protocols in quantum thermodynamics with an all-optical experimental setup, given that we can simulate two reservoirs at different temperatures with high control. In this scenario, the experimental discussion of the performance of quantum refrigerators [2, 3, 36] with optical devices and optical quantum thermometers [37, 38] are left as future research.

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