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Herbert F. Fotso, David Hucul, Kathy-Anne Soderberg, "Spectral control of quantum emitters in quantum information processing," Proc. SPIE 12205, Spintronics XV, 1220508 (3 October 2022); doi: 10.1117/12.2634113

Event: SPIE Nanoscience + Engineering, 2022, San Diego, California, United States

Invited Paper

Spectral Control of Quantum Emitters in Quantum Information Processing

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ABSTRACT

We demonstrate the use of external field protocols to control optical properties of quantum spins for optimized photon-mediated operations in quantum information processing. Specifically, we study two-photon interference operations between spectrally different quantum emitters with realistic control protocols. We show that, well beyond their idealized versions, appropriate external field protocols can suppress spectral diffusion, mitigate inhomogeneous broadening and restore photon indistinguishability between spectrally different quantum emitters. These protocols can play an important role in enabling more efficient light-matter interfaces that are essential for scalable quantum information processing platforms.

Keywords: Spectral Modulation, Hong-Ou-Mandel, Two-Photon Interference, Control Protocol

1. INTRODUCTION

A variety of systems have been successfully implemented as qubit modalities for quantum information processing. Each of these systems offers specific benefits and can be used advantageously for particular functions in a large-scale hybrid quantum platform. To this end, optimal light-matter interfaces to efficiently couple different quantum systems is essential.[1,2] While device manufacturing/engineering remains an important approach to a solution, processes to go beyond this solution will remain important either to mitigate residual spectral variations across nominally identical systems (e.g different quantum dots) or to enable efficient operations between different systems (e.g superconducting circuits and trapped ions or atoms). We have previously shown that spectral properties of quantum emitters can be controlled with external field protocols.[3–6] In addition, we have examined two-photon interference between different quantum emitters that can be hindered by spectral differences between the systems.[7] This problem is exacerbated in solid state systems where fluctuations in the surrounding environment lead to spectral diffusion.[8–10] In this paper, we propose to achieve experimental realization of pulse controls to enhance two-photon interference efficiency between spectrally different systems. We show that realistic external field protocols can perform desirable spectral modulation. In this way, well beyond their idealized versions, these protocols can restore photon indistinguishability between otherwise spectrally different quantum emitters and thus improve the efficiency of essential two-photon interference operations.

2. METHOD

We consider a quantum emitter in its most simple configuration where it can be represented by a two-level system (TLS) with ground state $|g\rangle$ and excited state $e\rangle$ separated by energy $E_e - E_g = \hbar\omega$. This system, in a radiation bath, is placed under the influence of an appropriately timed driving field. In the rotating wave approximation (RWA) and in the rotating frame so that all energies are measured with respect to the target frequency ω_0, the Hamiltonian describing the combined *emitter + radiation bath + external driving field* can be written as:[11]

$$H = \sum_k \omega_k a_k^\dagger a_k + \frac{\Delta}{2}\sigma_z - i\sum_k g_k \left(a_k^\dagger \sigma_- - a_k \sigma_+\right) + \frac{\Omega_x(t)}{2}(\sigma_+ + \sigma_-). \tag{1}$$

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Spintronics XV, edited by Henri-Jean M. Drouhin, Jean-Eric Wegrowe, Manijeh Razeghi,
Proc. of SPIE Vol. 12205, 1220508 · © 2022 SPIE ·
0277-786X · doi: 10.1117/12.2634113

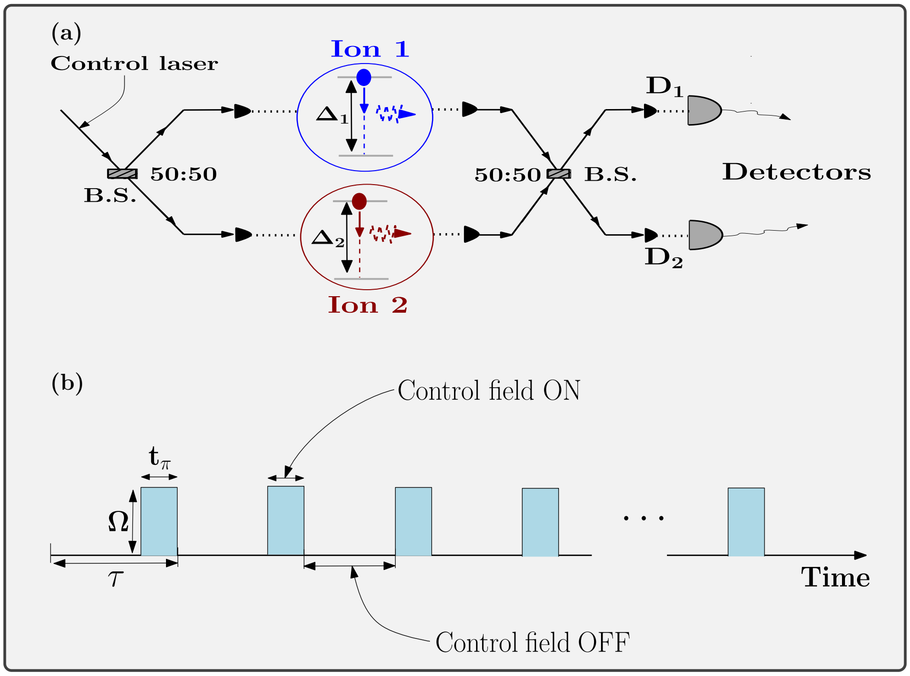

Figure 1. (a) Schematic for the proposed realization of pulse enhanced two-photon interference operation between two spectrally different systems. Photons from ions 1 and 2 are sent through a 50:50 beam splitter and then measured at the detectors D_1 and D_2. Both emitters are driven by a single control laser that has its beam divided by a 50:50 beam splitter. (b) The control laser at the Rabbi frequency Ω is tuned to apply a π pulse on the ions over a time t_π and the pulses are repeated with a period τ.

The operators $\sigma_z = |e\rangle\langle e| - |g\rangle\langle g|$, $\sigma_+ = |e\rangle\langle g|$, and $\sigma_- = |g\rangle\langle e| = (\sigma_+)^\dagger$ are respectively, the z-axis Pauli matrix, the raising, and the lowering operators for the two-level system. a_k ($a_k^\dagger$) is the annihilation (creation) operator of the k-th photon mode, g_k is its coupling strength to the emitter, and ω_k is the detuning from ω_0 of mode k. We consider pulses such that $\Omega_x(t) = \Omega_x = \Omega$ during the time t_π of the π-pulses and zero otherwise. For incomplete rotations, we only keep the finite value of Ω for a fraction of the time t_π. $\Delta = \omega - \omega_0$ is the detuning of the TLS's transition frequency from the pulse carrier frequency. All energies are measured in units of the free emission linewidth Γ and all times in its inverse $1/\Gamma$. We set $\hbar = 1$ in throughout this paper.

Our goal is to study the effect of external control protocols on the two-photon interference operation illustrated Fig.(1-(a)) for two spectrally different ions. The figure shows photons emitted by the respective ions that are sent through a 50:50 beam splitter and then measured at detectors D_1 and D_2. Both ions are driven by the same control laser that has its beam divided into two parts by a 50:50 beam splitter. Fig.(1-(b)) shows the time profile of the control laser that has a Rabbi frequency Ω and is applied for a time $t_\pi = \pi/\Omega$ and is appropriately switched on and off so that the sequence has a time period τ.

We study this system by numerically integrating the master equation that governs the time-evolution of the density matrix for the two-level system. The density matrix is :

$$\rho(t) = \rho_{ee}(t)|e\rangle\langle e| + \rho_{eg}(t)|e\rangle\langle g| + \rho_{ge}(t)|g\rangle\langle e| + \rho_{gg}(t)|g\rangle\langle g| \tag{2}$$

This solution produces correlation functions that allow us obtain both the emission spectrum and the cross-correlation function characterizing photon indistinguishability between the two system in a Hong-Ou-Mandel two-photon interference operation.[12]

3. RESULTS

We previously examined the emission/absorption spectrum of this system and the two-photon interference operation under the influence of a periodic sequence of idealized instantaneous π pulses with period τ. We found that the emission spectrum for a system with detuning Δ with respect to the pulse carrier frequency ω_0 features a central peak with the bulk of the emission spectrum at ω_0 and satellite peaks at $\pm\pi/\tau$[6] . In the context of the Hong-Ou-Mandel two-photon interference operation, we found that the sequence, when it is applied to two emitters with initially different detunings Δ_1 and Δ_2 restores photon indistinguishability and greatly improves the efficiency of the two-photon interference operation.[7] Here, we focus on assessing the robustness of the protocol when the pulses are altered away from their perfect limits (slow or incomplete rotations).

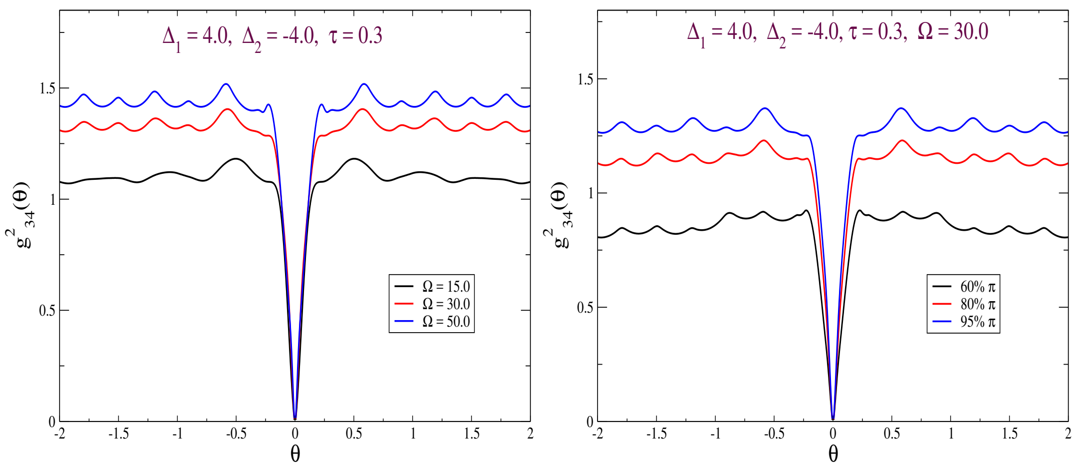

Figure 2. Cross-correlation functions as a function of delay time θ at the detectors. For emitters with respective detunings $\Delta_1 = 4.0$ and $\Delta_2 = -4.0$ driven by a sequence of period $\tau = 0.3$. Left panel: for rotations of duration $t_\pi = \pi/\Omega$ with Rabbi frequencies $\Omega = 15$ (black line), $\Omega = 30$ (red line), $\Omega = 50$ (blue line). Right panel: and for Rabbi frequency $\Omega = 30$ that is applied for a fraction of the time corresponding to a 60% π rotation (black line), 80% π rotation (red line), 95% π rotation (blue line).

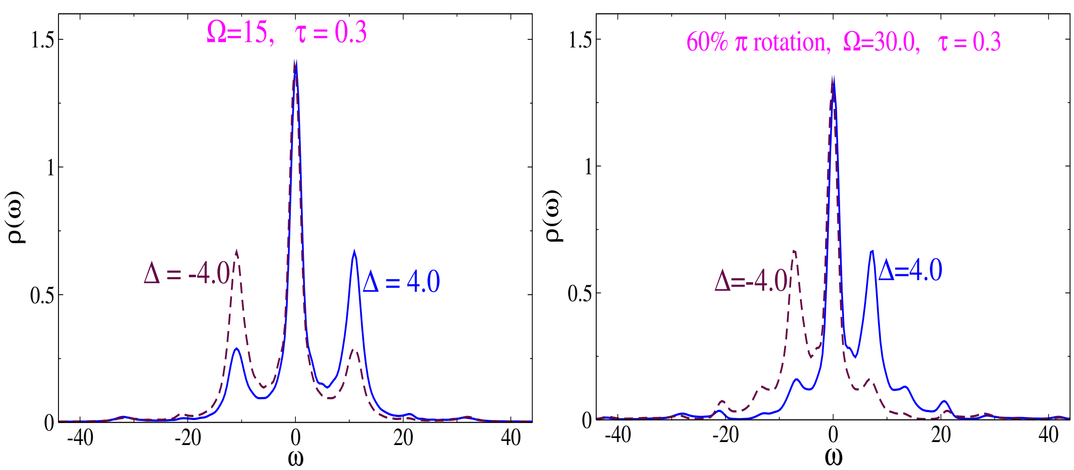

Figure 3. Emission spectra of the emitters with detuning $\Delta = 4.0$ (solid blue line) and $\Delta = -4.0$ (dashed brown line). Left panel: for emitters driven by a sequence of period $\tau = 0.3$ with finite width pulses of width $t_\pi = \pi/\Omega$ for a field with Rabbi frequency $\Omega = 15$. Right panel: for emitters driven with Rabbi frequency $\Omega = 30$ applied for time corresponding to a $60\%\pi$ rotation angle.

Fig.(2) presents the cross-correlation functions $g^{(2)}_{34}(\theta)$ as a function of delay time θ at the detectors for two driven emitters. *Ion 1* has detuning $\Delta_1 = 4.0$ and *Ion 2* has detuning $\Delta_1 = -4.0$. Left panel: the two emitters are driven with Rabbi frequencies $\Omega = 15$ (black line), $\Omega = 30$ (red line), $\Omega = 50$ (blue line). The inter-pulse delay is $\tau = 0.3$. Right panel: for the same detuning values, the emitters are driven periodically by a field with

Rabbi frequency $\Omega = 30$ that is applied for a fraction of the time t_π corresponding to a 60% π rotation (black line), 80% π rotation (red line), 95% π rotation (blue line). Note that in the absence of any control protocol, the cross-correlation function vanishes at time delay $\theta = 0$ but also periodically at times defined by the frequency difference between the two emitters. Note the deterioration with slower rotations and with further from complete rotations. Overall, the results are consistent with those of instantaneous pulses. Spectral overlap is restored and photon indistinguishability is restored even when $|\Delta_2 - \Delta_1| \sim 10\Gamma$.

Fig.(3) illustrates the enhancement of spectral overlap under the effect of the pulse sequences for two selected cases of broad pulse and incomplete rotation. Left panel: for π rotations with Rabbi frequency $\Omega = 15$ with sequence period $\tau = 0.3$. Right panel: for a 60% π-rotation with Rabbi frequency $\Omega = 30.0$ with inter-pulse delay $\tau = 0.3$. All results are shown after 12 pulses. Since in the absence of the control sequence the emission spectra would have Lorentzian lineshapes centered at the respective detunings and so would only overlap by a few percents, one notes the improved spectral overlap even with a far-from complete π rotation or for a very slow rotation.

4. CONCLUSION

Using the example of two spectrally different trapped ions, we have demonstrated that, consistent with instantaneous pulses, spectral modulation can be achieved with generally imperfect pulses (slow or incomplete rotations) and that this can in turn produce enhanced photon indistinguishability as measured by a Hong-Ou-Mandel experiment between two such systems. These results indicate that such protocols are fairly robust and may be of value for a variety of systems either to protect them from the environment or to tune their spectral properties for specific QIP operations.

ACKNOWLEDGMENTS

This work is supported by AFRL/RI under contract number SA10032022060524.

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