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How nonlinear optical effects degrade Hong–Ou–Mandel like interference

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ABSTRACT

Two-photon interference effects, such as the Hong–Ou–Mandel (HOM) effect, can be used to characterize to what extent two photons are identical [20]. Furthermore, these interference effects underly linear optics quantum computation. We show here how nonlinear optical effects, such as those mediated by atoms or quantum dots in a cavity, degrade the interference. This implies that, on the one hand, nonlinearities are to be avoided if one wishes to utilize the interference, but on the other hand, one may be able to measure or detect nonlinearities by observing the disappearance of the interference.
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1. Introduction

The Hong–Ou–Mandel (HOM) effect [17] is a celebrated example of a pure quantum interference effect. When two photons impinge on two different input ports of a 50/50 beamsplitter, the photons always emerge together in one of the two output ports. The destructive interference between the two paths that lead to the same final state with both photons exiting different output ports can be perfect only if at the output the two photons are indistinguishable. They must, in particular, have identical spectral and polarization states at the output. In principle there is no such requirement for the photons at the input, and HOM-like interference can occur, for example, between photons of different colors as well [26], provided there is a frequency-changing mechanism between input and output.

It is straightforward to describe the HOM interference effect in terms of creation operators, one for each electromagnetic field mode. If we denote the two relevant input operators of the 50/50 beamsplitter as $a_{\rm in}^\dagger$ and $b_{\rm in}^\dagger$ and the two corresponding output operators by $a_{\rm out}^\dagger$ and $b_{\rm out}^\dagger$, then we may write the effect of the 50/50 beamsplitter as a particular unitary transformation between the pairs of operators:

$$\begin{pmatrix} a_{\rm in}^\dagger \\ b_{\rm in}^\dagger \end{pmatrix} = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 & i \\ i & 1 \end{pmatrix}\begin{pmatrix} a_{\rm out}^\dagger \\ b_{\rm out}^\dagger \end{pmatrix}. \tag{1}$$

This description shows that an input state with two photons in input modes $a_{\rm in}$ and $b_{\rm in}$ is transformed into an output state of the form $((a_{\rm out}^\dagger)^2 - (b_{\rm out}^\dagger)^2)|{\rm vac}\rangle/2$, with the pair of photons always in a single output mode.

Any linear optics setup through which two photons travel affects a unitary transformation on the mode operators. The question we consider here is how *nonlinear* optics effects affect HOM interference. We consider this question in the context of coupled cavity arrays. Most research on coupled cavity arrays has focused on how classical light can be stored or delayed (there are more than a thousand papers in this area, see for example [33,16,15,29,1,19]), but such systems will be very useful for quantum communication purposes, too. In particular, such cavity arrays can be easily integrated with fiber optics, and they can be used to accurately introduce small time delays of single-photon wavepackets. One may expect cavity arrays to be used for entanglement purification protocols and quantum repeaters, which promise to increase the distance over which quantum key distribution can be securely employed [6,13]. This provides some additional motivation for studying this particular physical system.

We will include the generation of the two photons explicitly by assuming that we have two single emitters (which could be single atoms or single quantum dots or NV centers in diamond [28,22,8,27]), one in each of two cavities (see Fig. 1). This kills two birds with one stone: the two emitters will provide nonlinear

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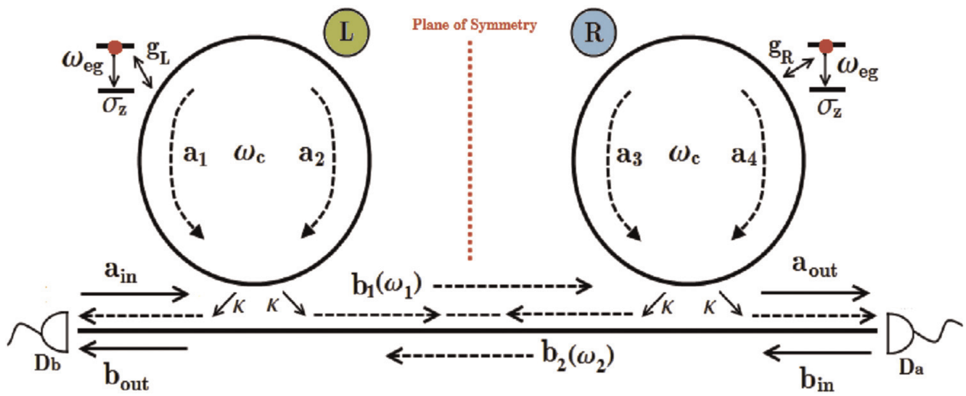

Fig. 1. Two spatially separated atom-cavity systems, and two single-photon detectors. Thanks to the bi-directional coupling between the two cavities, excitations can be transferred between the atom-cavity systems multiple times before being detected. We consider here a mirror-symmetric system, with all coupling constants, decay rates, and resonance frequencies pairwise the same for the left and right atom-cavity systems. The detectors count photons in the two output modes, described by annihilation operators $\hat{a}_{out}$ and $\hat{b}_{out}$. For further details, see main text.

optical effects, and the two photons whose interference effects we wish to study are automatically described realistically as wave packets. Note that the measurement of non-linearity in the present cavity-QED setup can be performed by following the procedures described in [9,18], which gives our work more experimental feasibility. The only work we are aware of in more or less the same direction as ours is a paper [24] on the HOM effect in a solid-state setup, with ambient noise taken into account, and with the two emitters included in the description, too (but no cavities, and hence no strong nonlinearities).

We describe our system and the theoretical methods we employ in Section 2. The description of unidirectional coupling of two cavities can be done elegantly within the formalism of quantum cascaded systems combined with quantum trajectories [4,12]. In our case we can still straightforwardly use the latter, but the former theory has to be adjusted to account for bidirectional coupling (so that the photons can travel back and forth between the two cavities). With the help of these methods, we study two-photon interference effects in Section 3. We simulate that there is an experiment in which one records which detector(s) detect the two photons, and at what times. The important information is then found in correlations between the two photon detections.

2. Two spatially separated atom-cavity systems

2.1. Model and Hamiltonian

We have two spatially separated atom-cavity systems (referred to as "left" or "L" and "right" or "R") coupled through an optical fiber which is assumed to have two continua of modes (propagating to the left and right), as shown in Fig. 1. A single photon is generated in each cavity through an initially excited atom (with transition frequency ω_{eg}: both atoms are taken to be identical in the rest of the paper). The spontaneous emission from the atoms is set to zero. In practice one suppresses the effects of spontaneous emission by using three-level atoms in the Λ configuration. The excited state can be eliminated adiabatically (it is only off-resonantly coupled), and the resulting description is that of an effective two-level system, where both levels are ground states.

Due to the atom-cavity coupling (represented by complex coupling coefficients g_L and g_R for left and right systems, respectively) the emitted photon can excite any one of the two counter propagating cavity modes, which are described by annihilation operators $\hat{a}_1$ and $\hat{a}_2$ for the left cavity, and $\hat{a}_3$ and $\hat{a}_4$ for the right cavity. Inside each cavity, both modes are assumed to have the same single resonant frequency ω_c.

There are two possibilities for the excitation to leak out of a given cavity. For example, for the left cavity, the photon in the mode $\hat{a}_2$ can exit towards the left (at a leakage rate κ) and will be detected by detector D_b. On the other hand, if the photon is in the mode $\hat{a}_1$, then it can escape towards the right (at the same leakage rate κ) after which it can enter into the right cavity due to the evanescent coupling between fiber and cavity. It may, alternatively, go straight to the detector D_a. Excitations can shuttle back and forth many times before finally being lost by the system and detected by the two detectors.

In our system there is a time delay τ between the cavities (which is defined in terms of the separation d between cavities as $\tau = d/c$, with c the group velocity of light in the fiber, which is assumed to be constant around the cavities' and atoms' resonant frequencies). Such time delays appear in the context of cascaded quantum networks [4,12] where they are considered arbitrary constants that can be eliminated, since they prove irrelevant to the physics of the problem. But for our system we cannot so simply ignore the time delay. This is due to the fact that the coupling between system L and R is not unidirectional. From this perspective our model resembles more a quantum feedback network [32,14], with the difference that there is no special part added to the actual system to perform this feedback [25,31]. Rather, this happens due to the geometry of the system itself.

Assuming no coupling between the intra-cavity modes and applying the standard rotating wave (RWA) and Markov approximations, the Hamiltonian of the global system (atoms, cavities and the fiber) takes the following form:

$$\begin{aligned}\hat{H}/\hbar = &-\omega_{eg}\hat{\sigma}_-^{(L)}\hat{\sigma}_+^{(L)} - \omega_{eg}\hat{\sigma}_-^{(R)}\hat{\sigma}_+^{(R)}\\ &+\omega_c(\hat{a}_1^\dagger\hat{a}_1 + \hat{a}_2^\dagger\hat{a}_2 + \hat{a}_3^\dagger\hat{a}_3 + \hat{a}_4^\dagger\hat{a}_4)\\ &+(g_L\hat{a}_1^\dagger\hat{\sigma}_-^{(L)} + g_L^*\hat{a}_1\hat{\sigma}_+^{(L)}) + (g_L^*\hat{a}_2^\dagger\hat{\sigma}_-^{(L)} + g_L\hat{a}_2\hat{\sigma}_+^{(L)})\\ &+(g_R\hat{a}_3^\dagger\hat{\sigma}_-^{(R)} + g_R^*\hat{a}_3\hat{\sigma}_+^{(R)})\\ &+(g_R^*\hat{a}_4^\dagger\hat{\sigma}_-^{(R)} + g_R\hat{a}_4\hat{\sigma}_+^{(R)}) + \int_{-\infty}^{+\infty}\omega_1\hat{b}_1^\dagger(\omega_1)\hat{b}_1(\omega_1)\,d\omega_1\\ &+\int_{-\infty}^{+\infty}\omega_2\hat{b}_2^\dagger(\omega_2)\hat{b}_2(\omega_2)\,d\omega_2\\ &+i\sqrt{\frac{\kappa}{2\pi}}\int_{-\infty}^{+\infty}(\hat{a}_1\hat{b}_1^\dagger(\omega_1) - \hat{a}_1^\dagger\hat{b}_1(\omega_1) + \hat{a}_3\hat{b}_1^\dagger(\omega_1)\\ &-\hat{a}_3^\dagger\hat{b}_1(\omega_1))\,d\omega_1\\ &+i\sqrt{\frac{\kappa}{2\pi}}\int_{-\infty}^{+\infty}(\hat{a}_2\hat{b}_2^\dagger(\omega_2) - \hat{a}_2^\dagger\hat{b}_2(\omega_2) + \hat{a}_4\hat{b}_2^\dagger(\omega_2)\\ &-\hat{a}_4^\dagger\hat{b}_2(\omega_2))\,d\omega_2.\end{aligned} \tag{2}$$

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