NONDEGENERATE TWO-PHOTON DOWN CONVERSION: COHERENT INPUTS AND NONCLASSICAL EFFECTS

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We study the nondegenerate two-photon down conversion described by a quantum trilinear Hamiltonian. The idler mode is initially prepared in the vacuum while the pump (laser) and the signal mode are prepared in coherent states which at high intensities resemble classical inputs. Such setup with a coherent signal mode allows us to scan the dynamics from the regime of the down conversion (empty signal) up to the frequency conversion (highly excited signal). The analysis concentrates on the entanglement properties of the modes which are compared with their other statistical properties such as squeezing and antibunching to give a more complete characterization of the modes. We show that the single mode nonclassical effects (squeezing and antibunching) disappear when an initial signal intensity highly exceeds that of the pump. In this regime the numerical results are confirmed by approximate analytical calculations. We point out that initially comparable intensities of the signal and pump mode lead to the effect of the “spontaneous disentanglement” of the signal mode from others and to the production of its squeezed and sub-Poissonian state which is pure to a good approximation.

1. Introduction

The study of nonclassical states of light [1,2], possible schemes for their generation as well as their realization [3] attracted great interest in recent years. One of the standard processes exhibiting interesting nonclassical effects, such as squeezing and antibunching, is the nondegenerate two-photon down conversion [4–10] associated with the generation of correlated photon pairs from a pump mode. In the common description the pump mode is treated classically, i.e., one does not consider any effect of the down-converted system on the state of the pump. A more detailed description of this process requires the inclusion of the quantum statistical properties of the pump mode. This more detailed quantum mechanical description is accepted as the primary one for the considered process and so a natural interest arises to compare these two treatments and to find conditions under which the description with a classical pump is consistent with the basic one. Therefore, our

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initial states will be coherent ones only, which at high intensities resemble classical inputs. Moreover, mainly these states are experimentally attainable as laser outputs. The processes studied in this paper correspond to the interaction of the three modes at exact resonance in a nonlinear crystal placed into a lossless cavity. The effective interaction between the modes is small in comparison with optical frequencies and thus the cavity serves to enhance the interaction time of the modes. In this setup the modes become strongly entangled [10].

One of the simplest and straightforward checks for the relation between the two descriptions of the pump mode is the look on behaviour of the pump. In the classical description the pump mode does not change its properties. When this is indeed the case, even for the quantum-mechanical treatment we have a first hint that the simpler description with a classical pump can be adopted instead of the fundamental (and more complicated) one. A simple measure which makes such check possible is the evaluation of the so called entanglement parameter [11] of the pump mode (another possibility is the use of the von Neumann entropy [12]). The entanglement parameter for the process of nondegenerate (as well as degenerate) down conversion [10,13,14] was studied recently for initial states covering a coherent input pump field. The down-converted modes were supposed to be in Fock states. It was shown that in general the modes involved in the interaction become strongly entangled, i.e., any particular mode loses its purity and transforms into a statistical mixture limiting thus the applicability of the parametric approximation to a short time scale. The term “parametric approximation” means representation of the intensive pump mode by a classical c-number. The results relevant to the validity of the parametric approximation can refer to any other elimination of the pump mode when the dynamics of the down-converted modes is described by an effective Hamiltonian.

In the nondegenerate two-photon down conversion [10] the restricted applicability of the parametric approximation was demonstrated for short times \( t \leq (\lambda \gamma)^{-1} \) when the signal and idler modes are initially empty and the pump mode starts from the coherent state \( |\gamma\rangle \) (\( \lambda \) denotes the coupling constant). Nevertheless, for a special choice of the initial state, the entanglement can remain small or for certain time periods even decreases to zero. Such behaviour is well known from the other fundamental nonlinear system, the Jaynes-Cummings model (JCM) [15–18], and occurs also in the studied system. Let us mention two known cases. In the case of an initial coherent pump, a vacuum idler and a strong number state in the signal mode the pump mode exhibits a much weaker entanglement of the pump mode to the down-converted modes [10]. This suggests a possible factorized description of the pump mode and the idler + signal subsystem by effective Hamiltonians on a time scale inversely proportional to the interaction constant \( \lambda \) which exceeds the region of small times. Therefore, one of our interests will be to test whether the same happens in the case when a number state of the signal mode is replaced by a corresponding coherent state, i.e. whether this behaviour depends on the signal mode statistics. The other case covers a situation when the down-converted signal mode is in a coherent state and the pump mode in a number state [14]. If the