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Ultrabroadband squeezed pulses and finite-time Unruh-Davies effect

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Abstract

We study the spectral properties of squeezed quantum light of ultrashort duration. In particular, we introduce a continuous multimode squeezing operator for the description of subcycle pulses of entangled photons generated by a coherent-field driving in a thin nonlinear crystal with $\chi^{(2)}$ susceptibility. We find the ultrabroadband spectra of the emitted quantum radiation perturbatively in the strength of the driving field. These spectra can be related to the spectra expected from the Unruh-Davies effect with a finite time of acceleration. In the time domain, we describe the corresponding behavior of the normally ordered electric field variance, which can be compared to the recent results obtained in quantum electro-optic experiments.

The nature of the quantum vacuum has been an actively studied and scientifically intriguing subject since the very early years of quantum mechanics. According to quantum field theory, the vacuum can be seen as an infinite set of harmonic oscillators in their ground states, each of them defining the vector potential (and thus the electric field) for a given wave vector and polarization. This infiniteness, however, renders extra complications to both theoretical and experimental studies involving the vacuum and its properties. Furthermore, the idea that a non-uniformly moving observer can perceive the vacuum as a populated state (Unruh-Davies effect) raises fundamental questions on the roles of entanglement, acceleration and causality in quantum phyiscs. Recently, a series of works [1, 2, 3] provided a deeper glance at the quantum structure of vacuum in an optical system by sampling and squeezing the fluctuations of the ground state of the electric field at a femtosecond time scale.

Following the respective works, the squeezing operator for an ultrabroadband (continuous) multimode squeezed vacuum state generated in a thin nonlinear crystal was derived. The squeezing is found to depend on the shape and duration of the driving coherent pulse generated via optical retification in a $\chi^{(2)}$ non-linear crystal. The spectral photon density distribution for such squeezed states can be calculated perturbatively and shows to a good accuracy an exponential decaying behavior for driving field shapes with fast enough decaying tails. We compare the corresponding spectra with the thermal-like spectrum of the Unruh-Davies radiation seen by a finite (laboratory-frame) lifetime observer moving with constant proper acceleration in Minkowski spacetime [4]. The temperature of the thermal radiation experienced by the accelerated observer depends inversely on his lifetime, which agrees with the inverse dependence on the driving pulse duration (i.e. refractive index modulation) seen for the spectra of squeezed vacuum [5]. Additionally, we analyse the temporal behavior of the normally ordered variance of the electric-field operator, which demonstrates both squeezing and anti-squeezing for different time intervals [6]. We show that the variance can be related to the world lines of the light modes propagating in the curved metric generated in the crystal through the Pockels effect.

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