

# Substantially squeezed states of light from a time flow perspective

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## Abstract

Light as a carrier of information and energy plays a fundamental role in both general relativity and quantum physics, linking these areas that are still not fully compliant with each other. Usually the quantum nature of light is described in the frequency domain. Even for broadband quantum states with a well-defined carrier frequency a quasi continuous wave picture is still applicable. However, recent access to subcycle quantum features of electromagnetic radiation promises a new class of time-dependent quantum states of light. Paralleled with the developments in attosecond science, these advances motivate an urgent need for a theoretical framework that treats arbitrary wave packets of quantum light intrinsically in the time domain. Here, we formulate a consistent time domain theory of the generation and sampling of few-cycle and subcycle pulsed squeezed states, leading to a relativistic interpretation in terms of induced changes in the local flow of time. Our theory enables the use of such states as a resource for novel ultrafast applications in quantum optics and quantum information.

The quantum nature of light possesses many astonishing properties rendering it a promising candidate for applications in many fields such as quantum spectroscopy or quantum information processing. Recently, electro-optic sampling was introduced as a new method to study these properties. This method allows for a detection of the fluctuations of the bare vacuum without the need of amplification. In the corresponding setup a few-femtosecond near-infrared probe pulse is sent through a thin electro-optic crystal where it mixes with the vacuum field modes in the mid-infrared range, imprinting the characteristics of the mid-infrared fluctuations on the signal [1, 2]. Furthermore, this technique is able to resolve the temporal profile of the variance of the probed field with subcycle resolution. As a result, this technique enables the study of non-classical states of light directly in the time domain. In a first step, it was possible to measure the time-resolved variance of a squeezed electric field, generated in a thin nonlinear crystal with a second-order susceptibility [3]. The emergent noise pattern consists of alternating intervals of squeezing and anti-squeezing.

We demonstrate theoretically that the quantum dynamics of the generated ultrabroadband squeezed light transients from thin nonlinear crystals can be determined for certain characteristic shapes of the driving few-cycle coherent waveforms and discuss the measuring process of these transients. Furthermore, the corresponding analytical solution allows for an insightful interpretation of the squeezing and anti-squeezing in terms of induced changes in the local flow of time and resulting redistribution of the quantum fluctuations. We show that this process can be connected to a broadband Bogoliubov transformation of the annihilation and creation operators, resulting from both parametric down-conversion and frequency conversion processes [4]. We predict that the conventionally observed asymmetry between squeezing and more pronounced anti-squeezing in the temporal noise traces, resulting from the product character of Heisenberg's uncertainty relation, can be reversed in the studied ultrabroadband case. We argue that this phenomenon can be realized under realistic conditions of the state-of-art experiments [5].

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