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Subcycle metrology of quantum electric fields

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Metrology of optical fields is at the heart of quantum signal processing, enabling quantum technology applications in communication, sensing and computing. Fast features are often of interest, yet traditional metrology of nonclassical signals is performed in the frequency domain via the technique of (balanced) homodyne detection (HD). In short, a signal-under-study is amplified by linearly superposing it with a strong classical local oscillator (LO) beam. While broadband LO can be used, the ultimate time resolution of HD is limited to the duration of the signal's envelope.

To enable measurement with a time resolution at the carrier wave period, the LO must provide access to subcycle timescale. With advent of femtosecond laser technology and ultrafast science, access to carrier frequencies from few THz to PHz and envelope durations down to a single cycle are now routinely available. An opportunity for subcycle detection therefore arises in the scenario when a few-cycle (e.g. near-infrared, NIR) pulse is superposed with a mid-IR (MIR) or a few-THz radiation. These two signals are brought into a frequency-domain superposition by mixing them in a nonlinear medium, where information on the instantaneous (subcycle) amplitude of the MIR-THz wave is carried in the polarization of the NIR probe beam – this measurement technique termed electro-optic sampling (EOS) [1-3].

Recently, EOS has been ported to the quantum regime. In particular, the variance of the broadband MIR quantum vacuum field has been directly measured through a careful analysis of the quantum-limited noise of the NIR probe, where the MIR vacuum contribution is manifested through an excess in the probe's noise beyond its inherent shot-noise threshold [4,5]. Since then, temporal structure of correlated vacuum, its two-time correlations and causal structure of the THz vacuum have also been experimentally accessed [6-8]. Full characterization of the quantum state requires access to both non-commuting quadratures and recent analysis demonstrates promising routes toward the measurement of both amplitude and Hilbert transform of the quantum signal in the subcycle regime [9,10].

A particularly elegant and a covariant approach to the measurement of both quadratures is yielded in the setup where bright entangled NIR beams replace the traditional classical EOS probe. A metrological advantage for the measurement of the amplitude quadrature has already been shown, harnessing the photon-number entanglement of the NIR probe pairs through the so-called band-conditioned states (BCS) of the probe [11]. In this presentation we propose a promising modification of the BCS scheme yielding simultaneous access to both quadratures and outlining a direct route toward subcycle quantum state tomography. Finally, we overview how these techniques can be ported into an integrated quantum photonics platform by utilizing nonlinear wave mixing in centro-symmetric media [12]. Combined, these collective developments are paving a path toward future realization of experimental subcycle quantum electrodynamics, motivating foundational studies [6,13] and time-domain quantum sensing applications.

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