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On-Chip Sub-Cycle Coherence Measurements of Sub-Terahertz Coherent States

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Abstract: We present an integrated photonic chip based on a thin-film lithium niobate platform that measures the autocorrelation function of coherent and non-coherent states of the terahertz electric fields with sub-cycle temporal resolution. © 2024 The Author(s)

1. Introduction

The temporal coherence of light is its ability to maintain a fixed phase relationship between temporally distant points [1]. Sources with long coherence times can therefore interfere with their delayed replica after propagating for a long distance opening doors for numerous applications in metrology and spectroscopy [2, 3].

The most common method for measuring temporal correlations of electric fields involves creating two time-delayed replicas of the field, interfering them in an interferometer, and recording the output intensity as a function of the delay using a quadratic detector that absorbs photons. However, this approach cannot measure correlations at distant spatial points, as it requires overlapping the fields, nor can it study states with zero photons, like the vacuum state, which do not produce detectable intensity. A direct method for measuring short- and long-range intra-cavity field correlations without an interferometer is therefore crucial for exploring the time- and space-resolved dynamics of light-matter interactions, including those driven by vacuum fields. [4, 5].

Electro-optic sampling (EOS) has recently emerged as a unique tool to study both the magnitude and correlations of both vacuum fields and classical thermal and coherent states in the mid-infrared and terahertz frequency range [6]. EOS relies on measuring the electric field of a state of light via the electro-optic effect introduced onto a femtosecond probe pulse. The spatio-temporal resolution of this electric field measurement is thus sub-cycle, limited by the spatio-temporal extent of the femtosecond probe pulse. So far, such measurements have been limited to bulk electro-optic crystals and inaccessible to exploring cavity-confined fields. This is mainly due to large mode and velocity mismatch between optical and terahertz radiation, which leads to low efficiency of electro-optic modulation. [4, 5].

In this work, we present an integrated photonic chip based on a thin-film lithium niobate platform that can overcome these shortcomings of conventional bulk realizations by implementing a terahertz cavity. In these devices, we measure the intracavity fields with a pair of optical probe pulses that are propagated along optical waveguides. We ensure phase matching between the terahertz and optical fields by carefully designing our terahertz cavity and the waveguide geometry, and the resulting fields overlap. It is important to note that the large transparency of thin film lithium niobate is essential to be able to record the two probes independently and reconstruct existing temporal correlations. We validate our concept by characterizing the first order correlation function of coherent states in the terahertz impinging from an off-chip source.

2. Results.

The geometry of the proposed devices is sketched in Fig. 1. An on-chip antenna receives the terahertz radiation directly from free space and couples it to an on-chip transmission line. The transmission line is designed to be around one of the Mach-Zehnder interferometer arms. Two optical pulses, separated by a time delay τ , are passed through our on-chip Mach-Zehnder interferometer. This geometry allows for the terahertz radiation confinement in the transmission line leading to the phase modulation of the optical pulses via the electro-optic effect. Thanks to the high electro-optic coefficient of the lithium niobate ($r_{33} \approx 33$ pm/V), such modulation is sufficient to probe weak terahertz fields. The phase modulation of each of the two pulses is then transformed into an intensity modulation in our interferometer where the phase modulated pulse interferes with its reference (unmodulated) pulse propagating along the second arm of the Mach-Zehnder interferometer. The intensity modulation $\Delta I/I$ is proportional to the phase induced by the terahertz radiation, which, itself is proportional to the terahertz electric field.

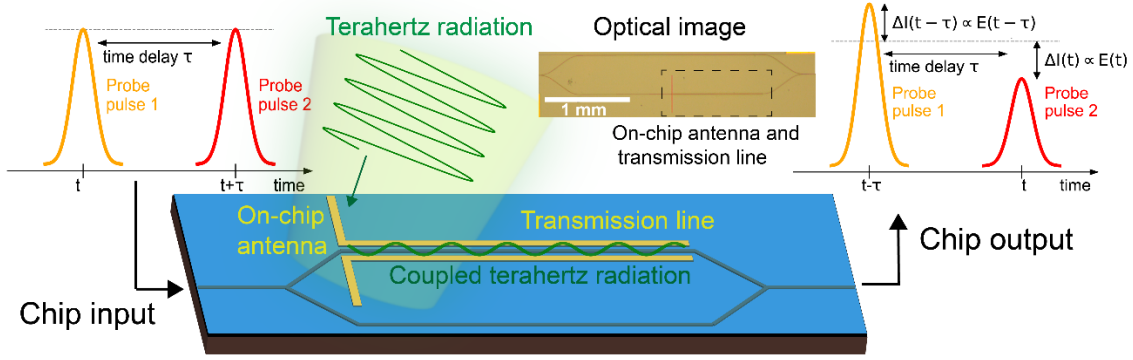


Fig. 1. Sketch of the device and the optical image of the device.

In order to obtain the first order correlation function $G^{(1)}(\tau)$, we split the two probe pulses after the chip, detect them with two photodiodes (PD). The voltages are read-out with a data acquisition card (DAC), and then digitally multiplied on a PC (Fig.2(a)). After averaging over multiple pulse pairs, one may obtain the first order correlation function $G^{(1)}(\tau)$, according to eq. (1):

$$G^{(1)}(\tau) = \langle E(t) \cdot E(t + \tau) \rangle_t \propto \langle \Delta I(t) \cdot \Delta I(t + \tau) \rangle_t \quad (1)$$

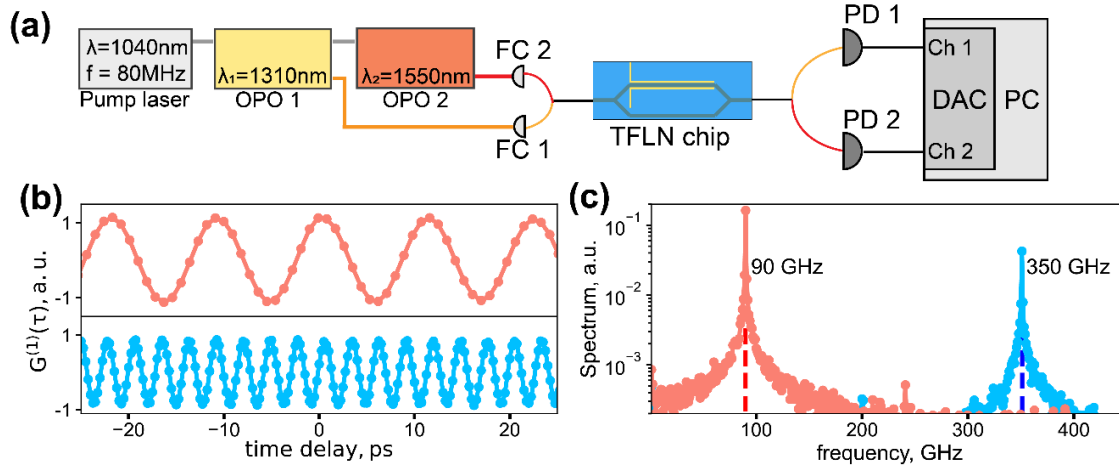


Fig. 2. (a) Sketch of the optical setup. OPO – optical parametric oscillator; FC – fiber coupler. (b) Measured autocorrelation function of coherent radiation at 90 GHz (upper subplot, red curve) and 350 GHz (lower subplot, blue curve). (c) The spectra of measured autocorrelation functions.

We finally measure the autocorrelation function of the coherent terahertz radiation at 90 and 350 GHz frequencies by delaying the pulses over 50 ps. The measured autocorrelation functions and their spectra are shown in Fig. 2(b)-(c). The acquired signals show the flat amplitude of the electric fields over multiple periods of the electric field oscillations. The building blocks we propose may enable quantum optics experiments that were recently proposed theoretically, such as performing sub-cycle state tomography, using quantum-optical probes, entanglement harvesting or correlations outside of the light cone [7, 8].

3. References

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