Terahertz quantum sensing with visible light

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***Abstract*— In quantum sensing experiments, photons in the spectral region of interest interact with a sample and their properties are transferred via biphoton-correlation to another spectral region, where widely available and highly developed detectors can be used. Especially spectral regions where the photon detection is quite difficult can benefit from this novel technique. We report on the first demonstration of quantum sensing in the terahertz frequency range, in which the terahertz photons interact with a sample in free space determining the thickness of polytetrafluoroethylene plates by only detecting visible photons [1].**

I. INTRODUCTION

IN the last decade, the principles of quantum sensing and imaging have become popular schemes for measurements in the infrared spectral range [2]. Those schemes are based on the technique of nonlinear interference in which pairs of correlated visible and infrared photons are generated at different locations by a nonlinear process. By overlapping each of the spectral components an interference can be observed for both. The advantage of this setup is that the interference in each spectral part does not only depend on itself, but also on the other. Consequently, changes in one of the spectral ranges has a direct impact on the interference in the other spectral range. The basis of this is the principle of induced coherence without induced emission [3].

The general principle of quantum sensing with terahertz radiation has previously been demonstrated by Kitaeva et al [4]. They used either a nonlinear interferometer in Young's geometry of one crystal or a Mach-Zehnder geometry of multiple crystals placed one after the other. In contrast to the infrared range, all mentioned setups for measurements with terahertz photons have in common, that the idler radiation is not coupled out of the nonlinear crystal, which is a crucial requirement for measurements of any external sample.

II. OBSERVATION OF QUANTUM INTERFERENCE WITH TERAHERTZ PHOTONS

In our experiment we use a single-crystal Michelson-like nonlinear interferometer with a 1-mm-long periodically poled MgO-doped lithium niobate (PPLN) crystal (see Fig. 1). The pump photons at 660 nm are focused into the nonlinear crystal generating correlated pairs of signal and terahertz photons caused by spontaneous parametric down-conversion and down-conversion as well as up-conversion of thermal photons. Afterwards, the pairs are separated by an indium tin oxide (ITO) coated glass. While the signal and pump photons are directly focused back into the crystal, the terahertz photons are first collimated with an off-axis parabolic mirror and subsequently reflected by a plane mirror placed on a piezo-electrical stage. In the second traverse of the pump photons through the nonlinear crystal again correlated pairs of signal and terahertz photons are created overlapping the pairs created in the first traverse. To obtain only signal radiation on the used sCMOS camera the pump radiation gets reflected at three volume Bragg gratings (VBG) acting as highly efficient notch filters. The remaining signal radiation is focused through a transmission grating onto the camera to acquire a frequency-angular spectrum [5].

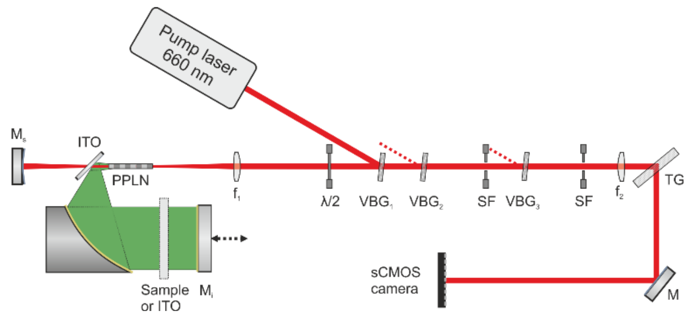

Fig. 1. The 660 nm pump source is reflected at a VBG (VBG1) into the setup through a zero-order half-wave plate ($\lambda/2$) controlling the polarization. The pump photons are focused by a lens f_1 into the 1-mm-long PPLN crystal generating signal and terahertz photons. The terahertz photons are split up from the pump and signal photons by an ITO glass. Signal and pump radiation are reflected directly back into the crystal while the terahertz radiation is first collimated and then reflected. In the second traverse of the pump through the PPLN, additional signal and terahertz photons are generated. After the second traverse the pump is filtered from the signal radiation by three VBGs. Afterwards the signal photons are focused by a lens f_2 through a transmission grating (TG) onto a sCMOS camera to acquire a frequency-angular spectrum.

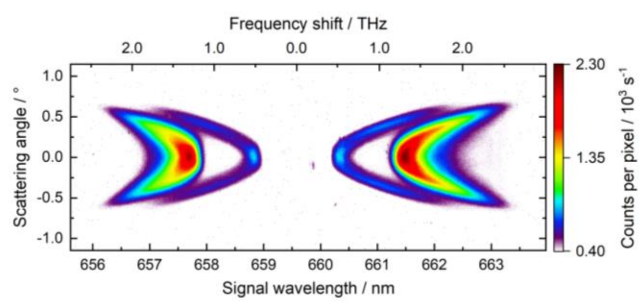

Fig. 2. Frequency-angular spectrum of the used 1-mm-long crystal (poling period $\Lambda = 90$ µm, pumped with 450 mW). The marked areas indicate where interference is occurring and the used colors match the following plots. The scattering angle corresponds to the angle after the transmission from the crystal to air.

The measured frequency-angular spectrum shows several tails caused by interaction with thermal terahertz photons at room temperature. After Raman-spectroscopy the region of down-converted photons is called Stokes and the region of up-converted photons is called anti-Stokes. Starting from the pump wavelength the tails with a lower frequency shift are connected to terahertz photons propagating in counter direction to the pump photons (backward). The more intense tails with higher frequency shifts stem from terahertz radiation propagating in the same direction as the pump (forward). Due to the experimental geometry, only for the forward tails an interference is observable as only here corresponding terahertz photons are getting reflected at the plane mirror in the terahertz path. Moreover, due to the large refractive index of the PPLN in the terahertz frequency range the terahertz radiation is coupled out of the nonlinear medium under large scattering angles compared to the visible photons. Therefore, only terahertz photons created under low scattering angles can be reflected back into the nonlinear crystal and interference can only be observed in the collinear forward regions of the signal radiation.

To observe an interference of the signal photons the position of the linear stage meaning the path length of the terahertz beam path is changed and a frequency-angular spectrum is recorded for each position and integrated in the collinear forward regions. In the Stokes as well as the anti-Stokes region an interference is visible. The observed interference has a visbility of less than 1 %. By placing an additional ITO-glass in the terahertz path the terahertz radiation is blocked while visible light propagating this path is transmitted. As Figure 3 shows, no interference can be observed in this case. Also in the corresponding fast Fourier transforms of the recorded measurements no significant amplitude is observable when the ITO glass is placed in the terahertz beampath whereas without the ITO glass an amplitude at about 1.26 THz is observable matching the calculated terahertz frequency for the specific poling length of 90 µm.

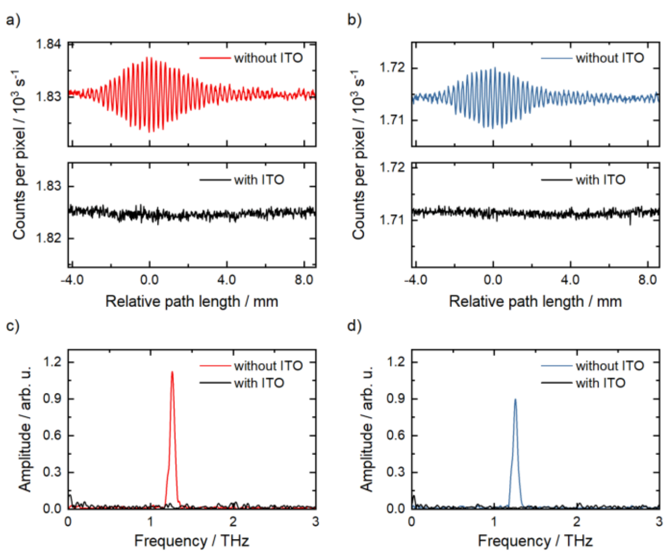

Fig. 3. In the collinear forward regions in the a) Stokes and b) anti-Stokes part of the frequency-angular spectrum, interference is observed by integrating the areas for each position of the translation stage that cannot be observed when an additional ITO glass is placed in the idler path. The corresponding FFTs c) and d) show peaks at about 1.26 THz and disappear when the ITO is placed in the idler path.

III. Demonstration of Layer-Thickness Measurement

To demonstrate the possibility of layer thickness measurement with terahertz radiation by detecting only visible photons, polytetrafluoroethylene (PTFE) plates with different thicknesses are placed in the idler path. PTFE is mainly transparent for terahertz radiation so the interference visibility is not decreased by the absorption of the sample but only by Fresnel reflections at the surfaces. Due to the changing refractive index by inserting a plate, the optical length of the terahertz path changes and the envelope of the interference shifts its position (see Fig. 4). Knowing the index of refraction of PTFE (n = 1.42) and the shift length caused by a double transmission through the sample allows the calculation of the layer thickness. For the used PTFE plates the measured layer thickness are in a good agreement with the layer thickness measured with a micrometer caliper.

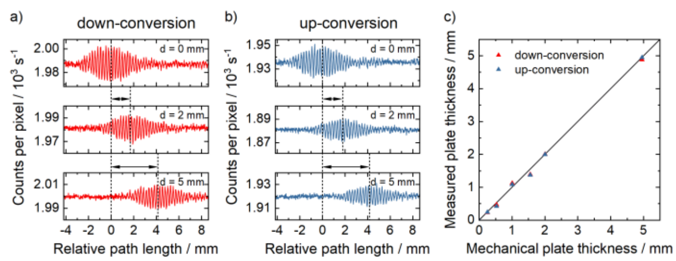

Fig. 4. Demonstration of terahertz quantum sensing with terahertz photons propagating in free space. The envelope of the interference is shifted depending on the thickness of the PTFE plate in the a) down-conversion and b) up-conversion part. c) Thickness d of the PTFE plate measured with terahertz radiation but detecting only visible photons over real thickness measured by a micrometer caliper.

IV. Summary

We observed quantum interference based on the effect of induced coherence with photons in the terahertz frequency range propagating in free space. It can be used to determine the layer thickness of samples placed in the terahertz path. To illustrate this, we show the first layer-thickness measurement with terahertz waves by detecting only visible photons.

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