Researchers demonstrate first terahertz quantum sensing

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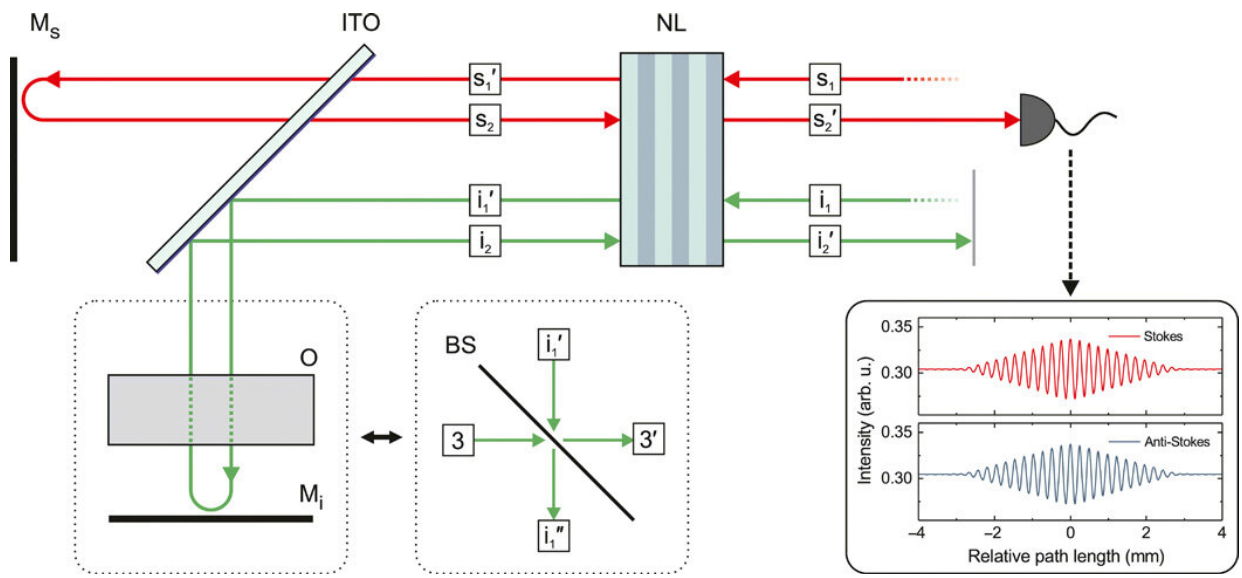
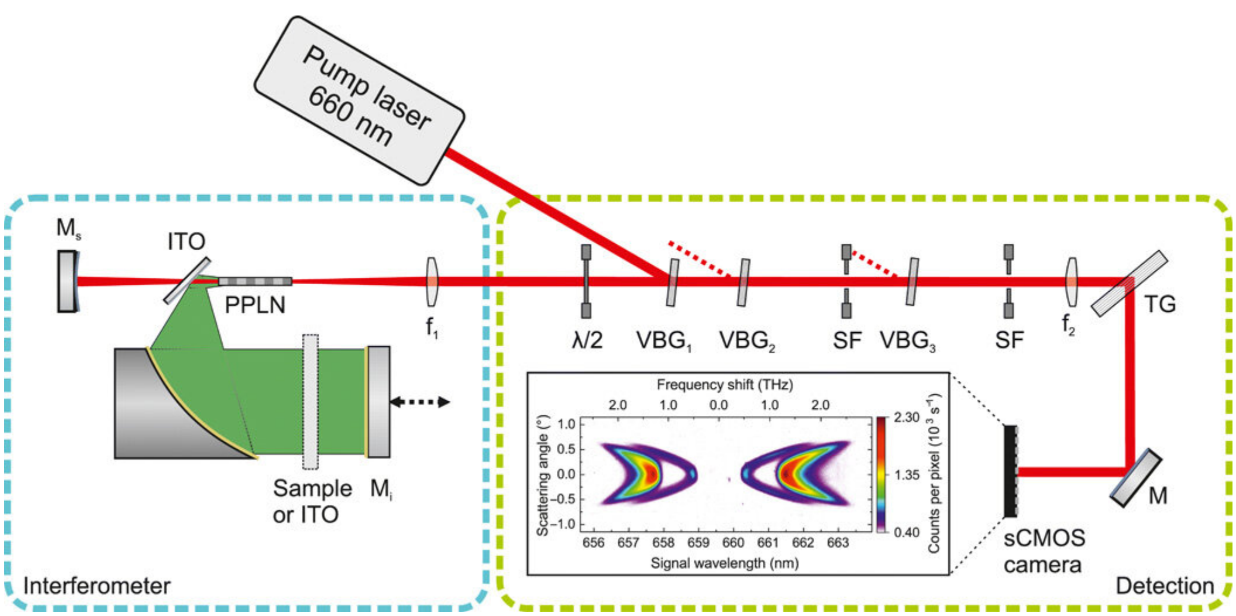


Scheme and nomenclature for the theoretical analysis. In addition to a laser pump (for simplification, not drawn here), the signal (s1) and idler (i1) input modes enter the nonlinear crystal (NL). The interaction in the crystal leads to the generation of signal and idler photons in the output modes s'1 and i'1, respectively. They are separated by an indium tin oxide (ITO)–coated glass. Afterward, the signal radiation and the pump beam are reflected back into the crystal by the mirror Ms. The input modes for the second passage are denoted by i2 and s2, which is, because of the alignment, equal to s'1. The idler mode i'1 passes through the object (O), is reflected by the mirror Mi, and propagates through the object again. This acts as a beam splitter (BS) with second input mode 3 and output modes i''1 and 3′. Aligning the idler beams, the mode i''1 corresponds to i2. The output modes after the second passage are s'2 and i''2. Last, the signal radiation (in mode s'2) is detected by the detector. The inset shows the simulated interference signal in the Stokes (red) and anti-Stokes (blue) regions based on the detailed model. Credit: Science Advances, doi: 10.1126/sciadv.aaz8065

Quantum physicists rely on quantum sensing as a highly attractive method to access spectral regions and detect photons (tiny packets of light) that are generally technically challenging. They can gather sample information in the spectral region of interest and transfer the details via biphoton correlations into another spectral range with highly sensitive detectors. The work is specifically beneficial for terahertz radiation without semiconductor detectors, where physicists must use coherent detection schemes or cryogenically cooled bolometers instead. In a new report on *Science Advances*, Mirco Kutas and a research team in the departments of industrial mathematics and physics in Germany described the first demonstration of quantum sensing in the terahertz frequency range. During the experiments, terahertz frequencies interacted with a sample in free space and provided information about the sample thickness by detecting the visible photons. The team obtained layer thickness measurements with terahertz photons based on biphoton interference. Since the ability to measure layer thickness non-destructively is of high industrial relevance, Kutas et al. expect these experiments to be a first step toward industrial quantum sensing.

Quantum sensing and imaging is a popular scheme for infrared measurements using a pair of correlated visible and infrared photons. Research teams had previously demonstrated the general principle of quantum sensing in the terahertz frequency range using a single-crystal interferometer in Young's configuration to measure the absorption of a periodically poled lithium niobate (PPLN) crystal, within the terahertz frequency range. In the present work, Kutas et al. generated terahertz (idler) photons using spontaneous parametric down conversion (SPDC) using pump photons at 660 km to generate signal photons at a wavelength of about 661 nm—very close to the spectra pump wavelength. To test the feasibility of quantum sensing at room temperature, the team first theoretically analyzed the concept for a single-crystal quantum interferometer.

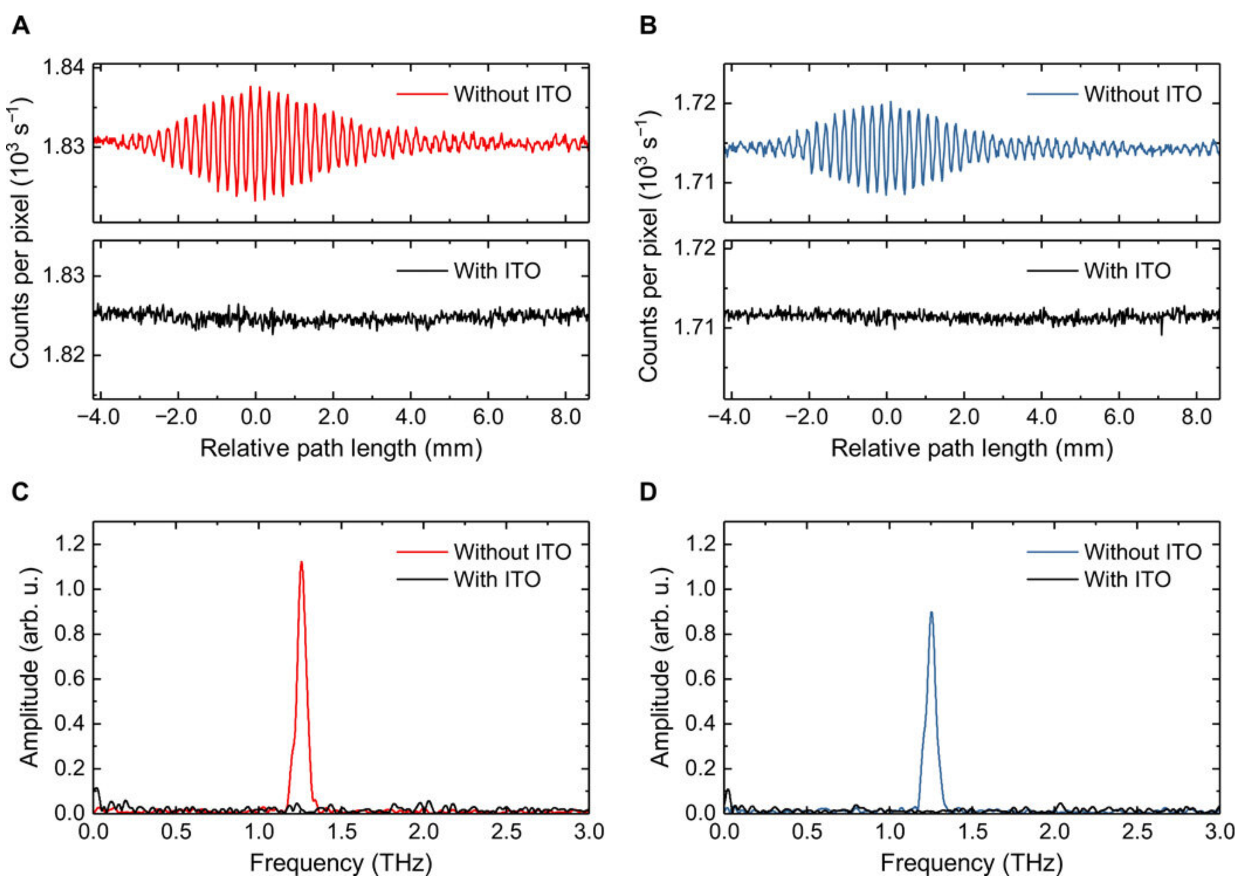
In theory, the setup contained a pump beam, which illuminated a nonlinear crystal to create pairs of signal (s) and idler (i) photons. Kutas et al. based their theoretical process on a previous study. In the usual SPDC (spontaneous parametric down conversion) experiments the input modes are in a vacuum state. However, in the present work the small energy of the idler photons in the terahertz range received substantial contributions from thermal fluctuations to be in a thermal state. During the experiment, the team expected to separate the pump and signal photons from the idler photons to interact with the object in order for the resulting radiation to be reflected and coupled back into the crystal. They illustrated the expected interference resulting from the model to conclude that an interference pattern could be expected in the presence of thermal photons for down-conversion (when the signal and idler fields have a lower frequency than the pump) as well as for up-conversion.



Schematic of the experimental setup. A continuous-wave laser with a wavelength of 659.58 nm is reflected by a VBG (VBG1) into the interferometer part of the setup through a zero-order half-wave plate (λ/2) controlling the polarization. It is then focused by a lens f1 into a periodically poled 1-mm-long MgO-doped LiNbO3 (PPLN) crystal generating signal and terahertz photons that are separated by an ITO. Signal and pump radiation are reflected at Ms directly into the crystal. The terahertz radiation passes the object twice, being reflected by a moveable mirror Mi. In the second traverse of the pump through the PPLN, additional signal and idler photons are generated. Afterward, the lens f1 collimates the pump and signal radiation for the detection starting with filtering the pump radiation by three VBGs and spatial filters (SF). To obtain the frequency-angular spectrum, the signal radiation is focused through a transmission grating (TG) by the lens f2 onto a sCMOS camera. The inset shows a frequency-angular spectrum for the used crystal (poling period Λ = 90 μm, pumped with 450 mW). The scattering angle corresponds to the angle after the transmission from the crystal to air. Credit: Science Advances, doi: 10.1126/sciadv.aaz8065

The present experimental setup was also based on a previously presented setup – extended to a Michelson-like single-crystal quantum interferometer. The scientists used a 660 nm frequency-doubled solid-state laser as a pumping source and coupled the photons to the interferometer using volume Bragg grating (VBG). For the nonlinear medium, they selected a 1-mm-long PPLN (periodically poled lithium niobate) crystal with a poling period of 90 μm to generate visible (signal) photons and associated (idler) photons in the terahertz frequency range. Behind the crystal, the researchers placed an indium tin oxide-coated glass to separate the idler photons from the pump and signal photons. They then directly focused the pump and signal radiation back into the crystal using a concave mirror.

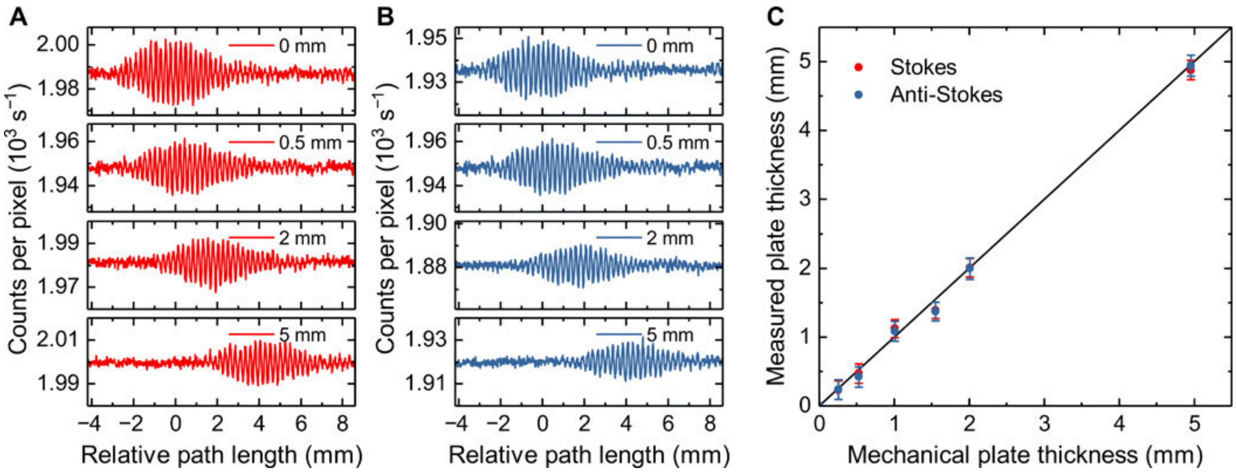
Since the refractive index of lithium niobate ($LiNbO_3$) in the terahertz frequency range led to a large scattering angle of the idler radiation, they collimated this radiation using a parabolic mirror and reflected the idler radiation at a plane mirror placed on a piezoelectric linear stage. After two passages through the crystal they collimated the pump and signal beams and filtered the pump photons using three VBGs that functioned as highly efficient and narrowband notch filters. The team used an uncooled scientific complementary metal-oxide semiconductor (sCMOS) camera as a detector. The signal photons in the setup could be generated either by SPDC (spontaneous parametric down conversion) or by converting the thermal photons in the terahertz frequency range. The signal intensity linearly depended on the pump power allowing the experiment to perform in the low-gain region.



Terahertz quantum interference. In the collinear forward spot of the signal, interference is observed in the (A) Stokes and (B) anti-Stokes regions. (C and D) Corresponding FFTs peaks at about 1.26 THz. By placing an additional ITO glass in the idler path, no interference can be observed, and the peaks in the FFTs disappear. Credit: Science Advances, doi: 10.1126/sciadv.aaz8065

The scientists observed the interference of the signal photons in the Stokes and anti-Stokes regions—matching the simulated interference signal. The corresponding fast Fourier transforms (FFTs) showed a peak during both instances relative to the phase-matching conditions. The noise of the recorded data resulted from laser fluctuations and the noise of the camera. To determine that the interference was caused by terahertz photons propagating along the idler path, they placed an indium tin-oxide glass between the parabolic and plane mirror, which blocked terahertz radiation, while allowing the transmission of visible light.

To then demonstrate terahertz quantum sensing, Kutas et al. measured the thickness of a variety of polytetrafluoroethylene (PTFE) plates—placed in the idler path with a maximum thickness of 5 mm. Due to the refractive index of PTFE, the optical length of the path changed and they observed the envelope of interference at different stages. Aside from the shift, the visibility of the interference decreased in the presence of the PTFE plate. The team detected the thickness of the plate by estimating their refractive index by using a standard time-domain spectroscopy (TDS) system. Based on the refractive index and shift of the interference signal they calculated the layer thickness. The results showed that the quantum interference with idler photons in the terahertz frequency range allowed the physicists to determine the layer thickness of samples in the terahertz path via quantum sensing.



Terahertz quantum sensing. The envelope of the interference is shifted depending on the thickness of the PTFE plate in the (A) Stokes and (B) anti-Stokes parts. (C) Thickness of the PTFE plate measured by quantum interference over PTFE thickness measured by a micrometer caliper. The solid line is the angle bisector. The horizontal error bars (hidden by the data points) consider the uneven thicknesses of the PTFE plates and the inaccuracy of the reference measurement. The vertical error bars result from the precision of determining the shift of the envelope center of the interference. Credit: Science Advances, doi: 10.1126/sciadv.aaz8065

In this way, Mirco Kutas and colleagues observed quantum interference in the terahertz frequency range with propagation of terahertz photons in free space, within the Stokes and anti-Stokes regions. They showed the capacity to use this technique to determine the thickness of a variety of PTFE regions as proof-of-concept applications in the terahertz frequency range. While the measurement time and resolution cannot be compared to classical terahertz measurement schemes, the concept presented here is a first milestone toward terahertz quantum imaging.

More information: Mirco Kutas et al. Terahertz quantum sensing, *Science Advances* (2020). DOI: 10.1126/sciadv.aaz8065

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