Terahertz Quantum Sensing

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Motivation

- **Quantum sensing** enables measurements in spectral regions inaccessible to classical photon detectors.
- Terahertz (THz) range is critical for industry (non-destructive evaluation, layer thickness, inspection) but detection is difficult.
- The work demonstrates **quantum sensing in the THz regime** via biphoton interference, transferring THz information to the visible spectrum.
- Conventional THz detectors suffer from low sensitivity and require cryogenic cooling, limiting practical applications.
- Quantum techniques allow indirect detection of THz properties using visible light, overcoming technological barriers.
- This approach opens new possibilities for material characterization, security screening, and biomedical imaging in the THz domain.

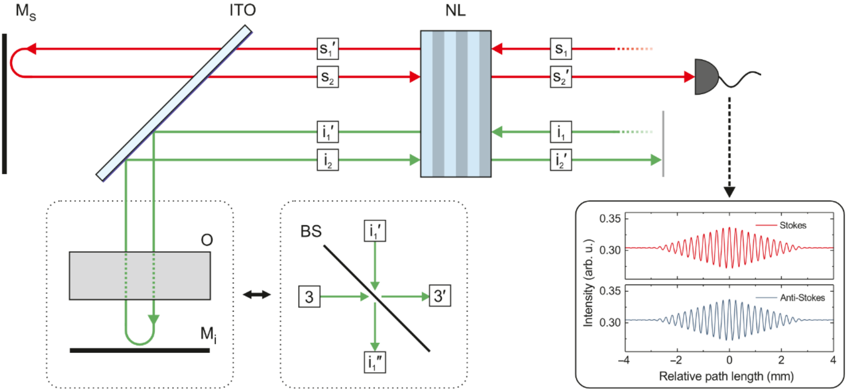
Principle

- Pairs of photons (signal, idler) generated by spontaneous parametric down-conversion (SPDC): signal in the visible, idler in the THz.
- SPDC process:

$$|1\rangle_p|0\rangle_s|0\rangle_i \Rightarrow \hat{a}_p\hat{a}_s^\dagger\hat{a}_i^\dagger|1\rangle_p|0\rangle_s|0\rangle_i = |0\rangle_p|1\rangle_s|1\rangle_i.$$

- Idler photon probes the sample; signal photon is detected.
- Quantum correlations between signal and idler photons enable extraction of sample information without direct THz detection.
- The measurement relies on interference effects, where changes in the THz path (due to the sample) are mapped onto the visible photon statistics.
- This principle allows for high-precision, non-contact measurements of sample properties such as thickness and refractive index.
- Interference of biphotons in a nonlinear crystal enables extraction of sample properties by observing only visible photons.

Diagram



Transformation of the annihilation operators with phase shifts:

$$\hat{a}_{i2} = \exp(i\phi_i)\,\hat{a}'_{i1} \qquad \hat{a}_{s2} = \exp(i\phi_s)\,\hat{a}'_{s1}$$

Theoretical Model

First pass:

$$a'_{s1} = u_1 a_{s1} + v_1 a_{i1}$$
$$a'_{i1} = u_1 a_{i1} + v_1 a_{s1}$$

Second pass:

$$a'_{s2} = u_2 a_{s2} + v_2 a_{i2}$$
$$a'_{i2} = u_2 a_{i2} + v_2 a_{s2}$$

Where u, v are conversion amplitudes for up- and down-conversion. and For $v_1 = v_2 = V_0$:

$$R_s = \langle \hat{N}'_{s2} \rangle = (N_{th} + 1) 2 V_0 [1 + \frac{1}{2} V_0 T + \frac{1}{2} V_0 + \sqrt{T(1 + 2V_0 + V_0^2)} \cos(2\phi)]$$

With sample:

$$R_s = (N_{\text{th}} + 1) 2 V_0 [1 + \cos(\phi_0 + \omega_i \frac{2x + (n-1)2d}{c})]$$

Comprehensive Theoretical Analysis

Effect of the Sample (Beamsplitter Transformation):

- The sample in the idler path acts as a beamsplitter:

$$a'_{i1} = ta_{i1} + ra_3$$

  where t, r are the transmission and reflection coefficients ($|t|^2 + |r|^2 = 1$).

- The sample introduces a phase shift: If the sample has thickness d and index n, the phase accrued by idler is $\phi = \omega_i nd/c$. a_3 is vacuum state.

Quantum Interference Condition:

- The interference signal for signal photon detection (after both passes) is:

$$R_s = \langle \hat{N}'_{s2} \rangle = (N_{th} + 1)2V_0[1 + \frac{1}{2}V_0 T + \frac{1}{2}V_0 + \sqrt{T(1 + 2V_0 + V_0^2)}\cos(2\phi)]$$

  where V_0 is gain, T sample transmission, ϕ accumulates all phase delays from cavity, optical path, and sample.

Comprehensive Theoretical Analysis (cont.)

Photon Generation and Quantum State:

- The quantum state after two passes (pump in both directions) is a coherent superposition:

$$|\Psi\rangle = N_1 \int d^3k_{s1} d^3k_{i1}\, f_1(\vec{k}_{s1}, \vec{k}_{i1})\, a^\dagger_{s1} a^\dagger_{i1} |0\rangle + N_2 \int d^3k_{s2} d^3k_{i2}\, f_2(\vec{k}_{s2}, \vec{k}_{i2})\, a^\dagger_{s2} a^\dagger_{i2} |0\rangle$$

where $N_{1,2}$ are proportional to the gain in each passage, and $a^\dagger_{s1} = a^\dagger(k_{s1})$.

Thermal State in THz (Idler) Mode:

- Unlike visible SPDC, the idler (THz) mode has non-negligible thermal occupation:

$$\langle n_{\text{th}} \rangle = \frac{1}{\exp\left(\frac{\hbar\omega_i}{k_B T}\right) - 1}$$

- Thermal photons play a direct role in signal production, particularly for up-conversion.

Stokes and Anti-Stokes Processes

- **Stokes Process:**
  - Downconversion where a high-energy pump photon splits into a *lower-energy* signal photon and an *idler* photon.
  - Energy relation: $\omega_{\text{pump}} = \omega_{\text{signal}} + \omega_{\text{idler}}$.
  - Signal photon wavelength is longer (lower frequency) than pump.
  - Commonly observed in spontaneous parametric downconversion (SPDC).
- **Anti-Stokes Process:**
  - Upconversion where a pump photon combines with an idler photon to form a *higher-energy* signal photon.
  - Energy relation: $\omega_{\text{signal}} = \omega_{\text{pump}} + \omega_{\text{idler}}$.
  - Signal photon wavelength is shorter (higher frequency) than pump.
  - Observed as the anti-Stokes sideband in quantum sensing, involving thermal THz photons.
- **Context in the Experiment:** Both processes contribute to the detected interference fringes in the signal photons, associated with Stokes (downconversion) and anti-Stokes (upconversion) spectral regions.

Nonlinear Michelson Interferometer: Experimental Setup

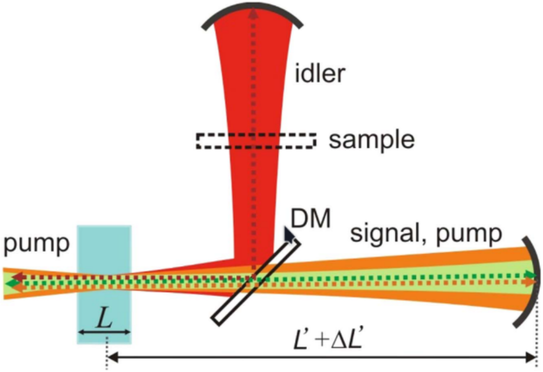


Figure: A nonlinear version of a Michelson interferometer. Signal and idler photons are generated via SPDC in a nonlinear crystal. The idler (terahertz, IR) and signal (visible) photons are separated by a dichroic mirror (DM). The sample is inserted in the idler path. Variable optical path length in the idler arm ($L' + \Delta L'$) enables phase scanning. Interference of signal photons is detected at the output.

How the Nonlinear Michelson Model Explains the Experiment

- The setup mimics a classical Michelson interferometer but uses quantum light: a nonlinear crystal generates entangled signal and idler photon pairs.
- The dichroic mirror (DM) splits the idler (THz) and signal (visible) photons into two arms:
  - **Idler Arm (vertical):** Contains the sample, introduces optical path change ($\Delta L'$), and reflects photons back through the crystal.
  - **Signal Arm (horizontal):** Signal photons are reflected and redirected back into the crystal with the pump.
- The phase accumulated by the idler photon in its arm (including any change from the sample) causes interference patterns in the detected signal photons—analogous to classical path difference fringes.
- This nonlinear approach enables probing of terahertz properties using visible photons by leveraging quantum interference, even without direct THz detectors.

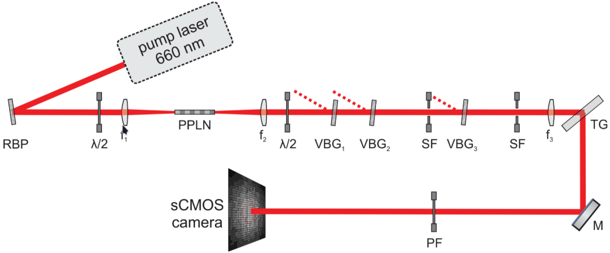


Figure: Old experimental setup

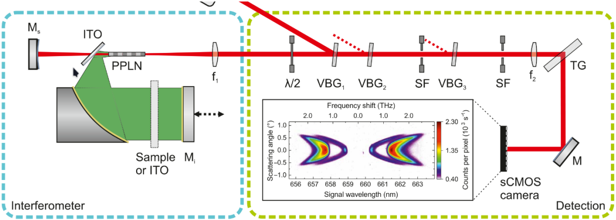


Figure: New experimental setup

Key Components and Experimental Setup

- **Volume Bragg Grating (VBG):** Narrowband optical filter suppressing pump laser light at 660 nm, transmitting signal photons efficiently.
- **Spatial Filter (SF):** Clean and optimize the spatial mode profile of the pump laser beam before it enters the nonlinear crystal.
- **Periodically Poled Lithium Niobate (PPLN):** Nonlinear crystal with poling period $\sim 90\,\mu m$ enabling efficient quasi-phase-matched SPDC of visible signal and THz idler photons.
- **Indium Tin Oxide (ITO) Coated Glass:** Used to block or modify the idler path for control experiments, verifying idler photon contributions.
- **sCMOS Camera:** Detects visible signal photons with high sensitivity and resolution without cryogenic cooling.
- **Dichroic Mirror (DM):** Separates idler (THz) and signal/pump (visible) beams for routing and detection.
- **Piezoelectric Linear Stage:** Precisely changes idler optical path length to scan interference fringes.

Results: Quantum Interference

- **Interference Observed:** Strong quantum interference fringes in signal photon counts are visible as a function of relative idler path length, both in (A) Stokes and (B) anti-Stokes regions (top panels, colored).
- **Role of Idler Path:** Inserting ITO glass in the idler arm completely removes the interference (lower panels, black), demonstrating that idler photons are essential for fringe formation.
- **Spectral Analysis:** FFTs (C and D) of the interference data display a clear peak at 1.26 THz without ITO; peaks vanish when ITO blocks the idler, confirming quantum-induced coherence at terahertz frequencies.

Quantum Interference: Experimental Data

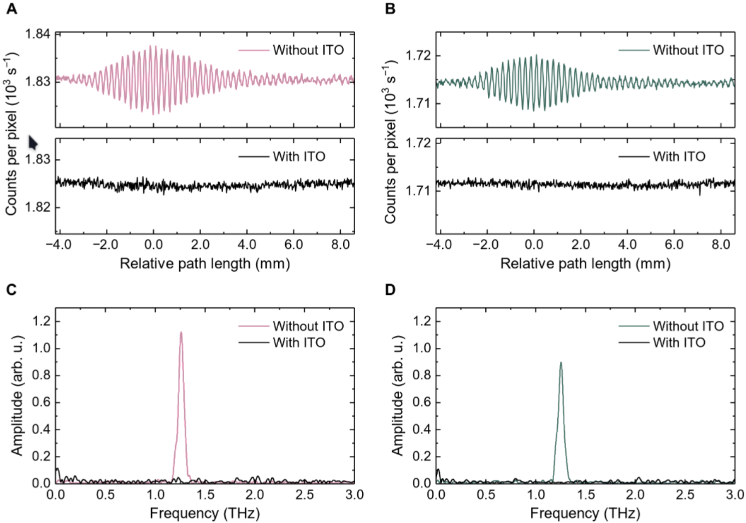


Fig. 3. Terahertz quantum interference. In the collinear forward spot of the signal, interference is observed in the (**A**) Stokes and (**B**) anti-Stokes regions. (**C** and **D**) Corresponding FFTs peaks at about 1.26 THz. By placing an additional ITO glass in the idler path, no interference can be observed, and the peaks in the FFTs disappear.

Results: Layer Thickness Measurement

- **Thickness Sensitivity:** Inserting PTFE plates of varied thickness into the idler path causes systematic shifts in the interference fringes (plots A and B; different plate thicknesses).
- **Quantitative Agreement:** The measured plate thickness from interference fringes closely matches mechanical micrometer values within a few percent, for both Stokes and anti-Stokes analyses (plot C).
- **Non-Destructive Measurement:** This confirms the method's accuracy and suitability for non-destructive, terahertz-range layer metrology using visible photon detection.

Layer Thickness Measurement: Experimental Data

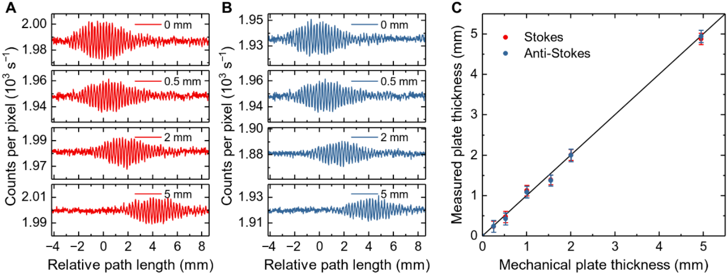


Fig. 4. Terahertz quantum sensing. The envelope of the interference is shifted depending on the thickness of the PTFE plate in the (**A**) Stokes and (**B**) anti-Stokes parts. (**C**) Thickness of the PTFE plate measured by quantum interference over PTFE thickness measured by a micrometer caliper. The solid line is the angle bisector. The horizontal error bars (hidden by the data points) take into account 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.

Fig. 3 (A-C bottom): Interference envelope (A,B) and quantum vs mechanical thickness correlation (C) with increasing plate thickness.

Discussion and Conclusion

Discussion:

- Interference depends on indistinguishability of photon origin (first vs second crystal pass), confirming induced coherence theory.
- Technique transfers information from hard-to-detect THz photons to visible photons for easy detection.
- Imperfections such as limited mode overlap and crystal absorption reduce visibility but do not eliminate the quantum effect.

Conclusion:

- First demonstration of quantum sensing in the terahertz range via biphoton interference.
- Enables nondestructive, precise layer measurements using visible photons only, avoiding direct THz detection.
- Establishes a foundation for practical quantum-enhanced industrial metrology and imaging.

M. Kutas et al., *Science Advances* 6, eaaz8065 (2020)