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Sensing a THz Electric Field with Cold and Trapped Molecular Ions

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Abstract: Comparison of two-photon rovibrational spectroscopy measurements of trapped and laser-cooled HD^+ ions with ab-initio quantum theory predictions may enable improved characterization of the amplitudes and phases of the Cartesian components of a THz electric field.

The electromagnetic fields may be characterized with high stability and accuracy by observing their effects on quantum objects under strict control of the internal and external degrees of freedom. Electromagnetically induced transparency of Rydberg atoms enabled detection of weak electric fields at the $\mu\text{V}/\text{cm}$ level with subwavelength resolution and sensitivity limited by the photon shot noise [1]. Doppler-free spectroscopy of trapped and sympathetically cooled HD^+ ions in a linear radiofrequency trap allowed recently significant improvements in accuracy and resolution [2,3]. Ab-initio quantum electrodynamics calculations provided accurate predictions for the HD^+ energy levels [4,5] and of their shifts in external fields [6,7]. This contribution proposes a new method to characterize completely the electric field of a THz-wave in a Cartesian reference frame based on comparison of the measurements of the lightshifts induced on a two-photon transition of HD^+ with the ab-initio theoretical predictions [8].

Precisely, the hyperfine components of the two-photon rovibrational transitions $(v,L)=(0,0)\rightarrow(2,0)$ or $(v,L)=(0,0)\rightarrow(2,2)$ of HD^+ may be measured in an ion trap by resonant enhanced multiphoton dissociation (Fig. 1(a)) with a ~ 2 Hz uncertainty estimated with the limit for the molecular ion quantum projection noise. The direction of the quantization axis of the HD^+ ions, defined with a static magnetic field that splits the Zeeman energy levels, is exploited to relate spectroscopic measurements to the parameters of the electromagnetic fields in a Cartesian reference frame. The comparison of the Zeeman spectroscopy results for a sensitive hyperfine component of the $(v,L)=(0,0)\rightarrow(2,2)$ transition with the theoretical predictions (Fig. 1(b)) allows to characterize the relative orientation of the coils that generate the magnetic field, the coil-to-field parameters, and the offset magnetic field. This procedure enables calibration of the orientation and strength of the magnetic field with uncertainties estimated at the mrad level and the 10^{-7} T level, respectively, for a magnetic field of 10^{-4} T.

A THz-wave slightly detuned to the Zeeman components of the $(v,L)=(0,0)\rightarrow(0,1)$ transition may be characterized by measuring the lightshifts induced on the $(v,L)=(0,0)\rightarrow(2,0)$ transition components. Using optimal detuning of the THz-wave enables detection of weak electric fields at the $\mu\text{V}/\text{m}$ level. The amplitudes and the phases of the Cartesian components of the THz electric field may be derived from six lightshift measurements for three calibrated values of the magnetic field and two orientations. The amplitudes of the components of the electric field of a linearly polarized THz-wave with an intensity of $1 \text{ W}/\text{m}^2$ slightly detuned to a hyperfine transition of HD^+ may be characterized with $\mu\text{V}/\text{m}$ -level uncertainties or better. The dependence of the root sum of squares of the uncertainties in function of the spherical

angles of the polarization vector is shown in Fig. 1(c). The uncertainties of the phases of the electric field components are at the mrad level or better [8].

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Figure captions

Fig. 1 (a) Energy levels of HD^+ probed in THz-wave sensing. Two-photon transitions (red lines), THz-wave driven electric dipole couplings (blue lines), dissociation (green lines). (b) Relative uncertainty of the magnetic field strength measurement by Zeeman spectroscopy of the $(v,L,F,S,J,J_z)=(0,0,1,2,2,-2)\rightarrow(2,2,1,2,4,0)$ transition. (c) Uncertainty in the characterization of a THz electric field using lightshift measurements of the $(v,L,F,S,J,J_z)=(0,0,1,2,2,2)\rightarrow(2,0,1,2,2,2)$ transition.

