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Christopher G. Wade

Terahertz Wave Detection and Imaging with a Hot Rydberg Vapour

Doctoral Thesis accepted by
Durham University, Durham, UK

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Supervisor's Foreword

The terahertz frequency range, loosely defined as the $0.1 - 10 \times 10^{12}$ Hz range, has long been considered a very difficult part of the electromagnetic spectrum to work in. This is because terahertz radiation lies in the frequency gap between electronic, microwave technologies and infrared, photonic technologies—the so-called terahertz gap. Nevertheless, much progress has been made over the last few decades to harness the advantageous properties of terahertz radiation. For example, terahertz (THz) waves are used in security, medical and biological applications because they are low energy and non-ionising but also pass through many materials, such as clothing, plastics and paper, that are opaque in the visible region. In addition, since the ro-vibrational transitions of many molecules lie in the THz range, the spectroscopic distinction of materials such as explosives and drugs can be performed.

In parallel to advances in THz systems, technologies based upon thermal atomic vapour have been developing and can now offer high performance across a wide range of applications. For example, magnetic field sensors and gradiometers based on thermal vapour cells can provide state-of-the-art sensitivity and also have a much-reduced experimental overhead when compared to laser cooling or cryogenic experiments, allowing inexpensive and robust implementation. Sensors based upon atomic samples are particularly attractive because they are 'pre-calibrated', in the sense that each atom of the same isotope is identical and their well-known properties can be traced back to SI units. This is probably best exemplified in the atomic clock, which provides the SI standard for time, frequency and length. However, despite the successes of atomic magnetometers and clocks, by comparison, the measurement of electric fields using atomic vapours is not so well developed.

It has long been known that, due to the loosely bound electron, atoms in highly excited 'Rydberg' states have extreme sensitivity to electric fields. Rydberg atoms also have many electric dipole transitions in the microwave and THz range making them particularly sensitive to electric fields across these frequencies. However, it was only a decade ago that sensitive optical detection of Rydberg atoms was made possible through pioneering work on 'Rydberg EIT' at the University of Durham. This work was followed quickly by significant technical development in the sensitive detection of RF and microwave fields using Rydberg atoms at the University of Durham, University of Oklahoma, NIST and elsewhere, thus paving the way for the work described in these pages.

This thesis presents pioneering work on the development of electric field sensing and imaging in the terahertz range using thermal atomic vapour. The basic idea is to map THz photons which are typically very difficult to detect, on to optical photons which are easy to detect. The thesis also explores the phenomenon of optical bistability and Rydberg phase transitions, where the optical properties of the atomic system change abruptly in response to a small change in control parameters. Using this phenomenon, it is demonstrated that the application of very weak terahertz fields can lead to large changes in the system response.

The thesis begins with a brief overview of THz technologies in Chap. 1 before providing a theoretical underpinning of the work, describing the physics of Rydberg atoms and atom–light interactions in Chap. 2. Chapter 3 introduces and describes the experimental setup before Chap. 4 details an experimental and theoretical investigation into probing an atomic excited state transition using quantum beats. Chapter 5 discusses results on Rydberg phase transitions and optical bistability, and terahertz electrometry is introduced in Chap. 6. Chapter 7 contains a study of terahertz imaging and Chap. 8 explores terahertz-driven phase transitions. A summary and outlook is presented in Chap. 9.

The results contained in this thesis have stimulated significant interest within academia and industry. The work could pave the way for a new class of room temperature sensors capable of real-time, stand-off and in-situ measurements across the terahertz range and have impact across a wide range of applications.

Durham, UK
April 2018

Kevin Weatherill

Abstract

This thesis investigates the resonant interaction between Rydberg atoms in a hot caesium vapour and terahertz frequency electromagnetic fields, and explores hyperfine quantum beats modified by driving an excited state transition in an inverted ladder scheme. The $21\mathrm{P}_{3/2}$ caesium Rydberg atoms are excited using a three-step ladder scheme and we use a terahertz field resonant with the $21\mathrm{P}_{3/2} \rightarrow 21\mathrm{S}_{1/2}$ transition (0.634 THz), to measure Autler–Townes splitting of a 3-photon Rydberg electromagnetically induced transparency (EIT) feature. The Autler–Townes splitting allows us to infer the terahertz electric field amplitude, and we show a worked example measurement of a low-amplitude electric field, yielding 25 ± 5 mV cm^{-1}.

By driving an off-resonant Raman transition which combines the laser and terahertz fields, we restrict the Rydberg excitation to areas of the caesium vapour where the laser and terahertz fields spatially overlap. We show that the terahertz field intensity is proportional to the pixel intensity of a camera image of the atomic fluorescence, and demonstrate an image of a terahertz standing wave. The camera image is used to fit a model for a corresponding Autler–Townes spectrum, giving the scale of the electric field amplitude, and we use a video camera to record real-time images of the terahertz wave.

In the regime of intrinsic optical bistability, we study a Rydberg atom phase transition and critical slowing down, and we find that the terahertz field drives the collective Rydberg atom phase transition at low terahertz intensity ($I_{\mathrm{T}} < 1$ Wm^{-2}). We measure a linear shift of the phase transition laser detuning with coefficient -179 ± 2 MHz W^{-1} m^{2}, and we use the frequency shift to detect incident terahertz radiation with sensitivity, $S \approx 90$ μW m^{-2} $\mathrm{Hz}^{-1/2}$. When the system is initialised in one of two bistable states, a single 1 ms terahertz pulse with energy of order 10 fJ can permanently flip the system to the twin state.

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