# Rydberg-atom detector conquers a new spectral frontier

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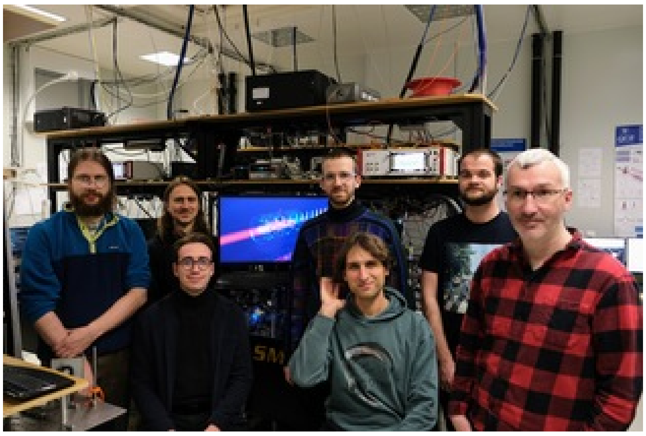
***A team from the Faculty of Physics and the Centre for Quantum Optical Technologies at the Centre of New Technologies, University of Warsaw has developed a new method for measuring elusive terahertz signals using a "quantum antenna." The authors of the work utilized a novel setup for radio wave detection with Rydberg atoms to not only detect but also precisely calibrate a so-called frequency comb in the terahertz band. This band was until recently a white spot in the electromagnetic spectrum, and the solution described in the prestigious journal Optica paves the way for ultrasensitive spectroscopy and a new generation of quantum sensors operating at room temperature.***


Authors of the work, from left: Jan Nowosielski, Mateusz Mazelanik, Bartosz Kasza, Wiktor Krokosz, Michał Parniak, Sebastian Borówka, Wojciech Wasilewski. (Photo by: Tomasz Prokop University of Warsaw).

Terahertz (THz) radiation, being part of the electromagnetic spectrum, lies at the boundary of electronics and optics, positioned between microwaves (used, for example, in Wi-Fi) and infrared. Although it holds immense potential—from inspecting packages without harmful X-rays, through superspeed 6G communication, to spectroscopy and imaging of organic compounds—its practical use for precise and sensitive measurements remains a significant technical challenge. Recent years have brought enormous progress in both the detection and generation of this radiation, but the precise measurement of a frequency comb has not been achieved until now.

Why is this so important? Frequency combs, which earned a Nobel Prize in 2005, are most easily visualized as an extremely precise ruler, but one created from light or radio waves. Instead of millimetre markings, one has a series of uniformly spaced lines ("teeth") at strictly defined frequencies. This "electromagnetic ruler" allows physicists to measure the frequency of an unknown signal with extreme accuracy—simply by checking which "tooth" on the ruler the signal aligns with. As a result, combs serve as a reference standard for calibrating and tuning other devices across a very wide range. Depending on where in the electromagnetic spectrum this ruler is located, we refer to optical, radio, or terahertz frequency combs.

Terahertz frequency combs are particularly interesting because they would enable calibration and, consequently, more precise measurements in a frequency range significantly higher (faster oscillating) than radio waves, yet lower than optical waves (light). However, this type of comb is difficult to measure precisely—it is too fast for modern electronics and, at the same time, cannot be recorded with optical methods. Although the spacing between the comb's teeth can be determined, and the total power emitted across the spectrum can be measured, it has been challenging to determine the power contribution of a single tooth.

The scientists from the Faculty of Physics and the Centre for Quantum Optical Technologies at the Centre of New Technologies, University of Warsaw successfully overcame this limitation and measured the signal emitted by a single terahertz comb tooth for the first time. To do this, they used a gas of rubidium atoms in a Rydberg state. A Rydberg atom is defined as having a single electron excited to a very high orbit by being illuminated with precisely tuned lasers. This "swollen" atom becomes a quantum antenna, extremely sensitive to external electric fields. Furthermore, using tunable lasers, it can then be tuned to one specific frequency of such a field, in a range extending up to terahertz waves.

Traditionally, in Rydberg electrometry, the phenomenon of Autler-Townes splitting is used to measure the electric field. Its huge advantage is that the measurement result depends only on fundamental atomic constants, providing an absolutely calibrated readout. Unlike classical antennas, which require laborious calibration in specialized radio laboratories, the atomic-based system is, in a sense, a standard unto itself. Moreover, thanks to the richness of energy states in the atom, such a sensor can be tuned almost continuously over an enormous range—from a direct current (DC) signal up to the aforementioned terahertz.

However, this method has a limitation: on its own, it is not sensitive enough to record very weak terahertz signals. To remedy this, the research team additionally applied a radio wave-to-light conversion technique invented at the University of Warsaw and adapted it to the needs of terahertz radiation. In this process, the weak terahertz signal is converted into optical photons, which can then be detected with immense sensitivity using single-photon counters. This hybrid approach is the key to success: it combines the extreme sensitivity of photon detection with the ability to "recover" the calibration capabilities of the Autler-Townes method even for the weakest signals.

The sensor based on Rydberg atoms possesses all the features needed to perform precise frequency comb calibration: it can be tuned to a single tooth of the comb, and then retuned to the next, and the next. The scientists managed to observe several dozen teeth in a very wide frequency range this way. Additionally, thanks to the knowledge of the fundamental properties of atoms, the comb was directly calibrated, precisely determining its intensity.

The results obtained by the physicists from the University of Warsaw Wiktor Krokosz, Jan Nowosielski, Bartosz Kasza, Sebastian Borówka, Mateusz Mazelanik, Wojciech Wasilewski, and Michał Parniak are more than just another sensitive detector. They are the foundation for a new branch of metrology. Thanks to the advantages of Rydberg atoms, the revolutionary applications of optical frequency combs can now be transferred to the hitherto difficult terahertz domain. Crucially, unlike many quantum technologies requiring extremely low temperatures, the developed system operates at room temperature, which drastically reduces costs and facilitates future commercialization. This opens the door to creating reference measurement standards for the upcoming era of terahertz technologies.

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**Faculty of Physics at the University of Warsaw**
Physics and astronomy at the University of Warsaw appeared in 1816 as part of the then Faculty of Philosophy. In 1825, the Astronomical Observatory was established. Currently, the Faculty of Physics at the University of Warsaw consists of the following institutes: Experimental Physics, Theoretical Physics, Geophysics, the Department of Mathematical Methods in Physics. The research covers almost all areas of modern physics on scales from quantum to cosmological. The Faculty's research and teaching staff consists of over 250 academic teachers. About 1350 students and over 150 doctoral students study at the Faculty of Physics UW. The University of Warsaw is among the 200 best universities in the world, educating in the field of physics according to Shanghai's Global Ranking of Academic Subjects.

## SCIENTIFIC PUBLICATION:

W. Krokosz, J. Nowosielski, B. Kasza, S. Borówka, M. Mazelanik, W. Wasilewski, M. Parniak Electric-field metrology of a terahertz frequency comb using Rydberg atoms, Optica Vol. 12, Issue 11, pp. 1854-1864 (2025)
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Website of the Centre for Quantum Optical Technologies QOT UW

**GRAPHIC MATERIALS:**

**FUW251205b_fot01**
https://www.fuw.edu.pl/tl_files/press/images/2025/FUW251205b_fot01.png
Frequency comb converted into light by a cell with Rubidium atoms. (Image authors: Mateusz Mazelanik University of Warsaw, Wiktor Krokosz University of Warsaw).

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Authors of the work, from left: Jan Nowosielski, Mateusz Mazelanik, Bartosz Kasza, Wiktor Krokosz, Michał Parniak, Sebastian Borówka, Wojciech Wasilewski. (Photo by: Tomasz Prokop University of Warsaw).

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