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Quantum radio antenna

A team from the Faculty of Physics and the Centre for Quantum Optical Technologies at the University of Warsaw has developed a new type of all-optical radio receiver based on the fundamental properties of Rydberg atoms. The new type of receiver is not only extremely sensitive, but also provides internal calibration, and the antenna itself is powered only by laser light. The results of the work, in which Sebastian Borówka, Mateusz Mazelanik, Wojciech Wasilewski and Michał Parniak participated, were published in the prestigious journal Nature Communications. They open a new chapter in the technological implementation of quantum sensors.

In today's society, huge amounts of digital information are transmitted around us every second. Much of it is transmitted by radio, i.e. using electromagnetic waves. For a very long time, amplitude modulation has been used to encode information, sending stronger and weaker waves. In newer protocols, we also change the phase of the waves, i.e. the delay of their vibration relative to the agreed clock cycle. Every modern transmitter and receiver is equipped with precise metronomes that determine the clock cycle used to transmit and decode waves – in technical jargon, this is referred to as superheterodyne detection.

Information hidden in waves

These technologies can be easily explained using an analogy. Prof. Wojciech Wasilewski suggests imagining the reception of sea waves: in order to receive the information encoded in the waves while standing on the beach, one must note both the strength of the waves – how deeply they wash onto the beach – and the exact moments when the waves hit the shore. The same applies to "transmitting" waves with a teaspoon in a cup of tea: if we were a WiFi transmitter, the teaspoon would have to be dipped at a steady rhythm, in time with the control circuits. However, we should not act immediately at every call, but with a delay, each time exactly the same. Once every few thousand periods, we would have to change the depth and delay – the part of the beat at which we dip the teaspoon. This would give us quadrature amplitude modulation (QAM).

In practice, metal antennas are commonly used to receive transmissions, which redirect the energy of incoming waves to the receiver. Energy absorption enables electronic measurement of the amplitude and phase of the waves. Today, this measurement is performed by converting (mixing) frequencies. The electrical signal from the antenna, which vibrates billions of times per second (at a gigahertz frequency), is directed to so-called mixers, which enable demodulation – the transfer of the amplitude and phase of very fast vibrations to signals with a lower frequency, vibrating only millions of times per second (at a megahertz frequency). At this stage, it is possible to easily separate adjacent channels that we do not want to receive. Modern electronics can easily perform digital voltage measurements tens of millions of times per second. These measurements are used to reconstruct the full waveform of the vibrations and, with the help of digital signal processing algorithms, their amplitude and phase.

Synchronised dance of atoms

As Dr. Michał Parniak explains, "in our experiments, **we replaced the antenna and electronic mixer with a new medium** – a kind of artificial aurora borealis". A piece of rubidium was placed in a glass cell, which had been thoroughly pumped out of air. Then atoms were released from the piece of rubidium and flew into the glass cell. They were then harnessed for a carefully planned performance. Each rubidium atom has one fairly free electron, which is subjected to a complex choreography of dancing around the atomic nucleus and core composed of the remaining 36 electrons. Three different lasers act as music in this dance. Their vibration frequency is ultra-precisely stabilised to the possible frequencies of electrons orbiting in rubidium atoms, as determined by the laws of quantum mechanics. The electrons "hear" such a "melody" that they spend selected parts of the laser dance beats in a very, very distant orbit – in so-called Rydberg states. In these orbits, their trajectory is very easily curved by microwaves. Specifically, by radio waves that are in rhythm with the laser melody being played. However, each electron in a Rydberg state – elevated to a high orbit – cannot remain there indefinitely and must eventually fall like a decommissioned satellite. Electrons affected by radio waves fall along a different trajectory and emit infrared radiation different from that used by lasers, making them easy to detect. Most importantly, the phase of the microwaves is reflected in the phase of the emitted infrared radiation: if the radio waves have "struck" earlier within a set cycle, the electrons also fall slightly earlier and emit radiation earlier.

The challenge that was solved in the latest publication was to build a system for precisely controlling the lasers and the dance of electrons so that the rhythm of the electrons' movement never slowed down or accelerated in an uncontrolled manner. For this purpose, a series of "metronomes" were used. For each laser, a special vacuum tube was constructed, terminated with very good mirrors, with which light is reflected several thousand times. Such a tube, called an optical cavity, like an organ pipe or a violin string, selects only vibrations of a specific frequency. In the tubes used here, two fields vibrate simultaneously – a stabilised laser and a reference laser, whose frequency is precisely electronically matched to the period of the lowest orbit in which electrons can orbit the nucleus and core of rubidium. In addition, a special crystal is used to mix frequencies to produce reference infrared radiation from the lasers used. The crystal is not sensitive to microwaves, so the infrared it emits has a slightly different frequency than that emitted by rubidium atoms. Practical measurement required the use of an additional reference laser, against which the infrared emitted from the atoms and the reference infrared from the mixing crystal were measured. Such a relative measurement – an optical heterodyne – made it possible to obtain the amplitude and phase of the fields under study. In turn, these can be used to directly calculate the amplitude and phase of the received microwaves.

Undetectable detection of radio fields

At the heart of the experiments presented, i.e. in the rubidium cell, **there are no metal elements that conduct electricity and strongly disturb radio waves**. All that is needed to convert radio waves into infrared radiation is rubidium vapour, a sealed enclosure and lasers. In the future, the detector could take the form of a mere thickening on an optical fibre, through which all the necessary lasers will be supplied, as well as the received infrared radiation, sent in the opposite direction in the optical fibre. The final measurements and corrections will be carried out even several dozen metres away from the radio fields, enabling extremely discreet, non-invasive measurement and reception of the radio field.

This invention may have serious consequences for the techniques of precise calibration of microwave fields. Thanks to non-invasive measurements, it will be possible to record weak fields without simultaneously disturbing them with a metal antenna. It is also possible to imagine such a microwave sensor being perfectly concealed as a wiretap device. Unlike currently available electronics, it would be much more difficult to detect as a receiver of any radio transmissions.

Scientists at the Centre for Quantum Optical Technologies and the Faculty of Physics at the University of Warsaw have been designing and demonstrating new protocols for detecting microwave fields using Rydberg atoms for several years. The team is succeeding in overcoming technical barriers and developing new detection methods offered by these revolutionary devices. The scientists are participating in the search for applications for this new technology, pointing to its ease of calibration, high sensitivity and measurement accuracy, and the prospect of miniaturisation of the devices. The rapid technological development is attracting the interest of foreign and international measurement standardisation agencies, military institutes and space agencies, which are planning to place Rydberg sensors on satellites in the future. Since the beginning of 2025, the team led by Dr. Michał Parniak has also been commercialising this technology in a project commissioned by the European Space Agency.

The research is also one of the central results of the SONATA17 project financed by the National Science Centre, Poland.

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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, and the Astronomical Observatory. 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 1000 students and over 150 doctoral students study at the Faculty of Physics UW. The University of Warsaw is among the 300 best universities in the world, educating in the field of physics according to Shanghai's Global Ranking of Academic Subjects.

SCIENTIFIC PUBLICATION:

S. Borówka, M. Mazelanik, W. Wasilewski, M. Parniak
Optically-biased Rydberg microwave receiver enabled by hybrid nonlinear interferometry
Nature Communications (2025)
https://www.nature.com/articles/s41467-025-63951-9
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GRAPHIC MATERIALS:

FUW251016b_fot01
https://www.fuw.edu.pl/tl_files/press/images/2025/FUW251016b_fot01.png
Experimental setup for controlling the quantum radio antenna *(photo Michal Parniak, University of Warsaw)*

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https://www.fuw.edu.pl/tl_files/press/images/2025/FUW251016b_fot02.png
All-optical quantum radio antenna – a rubidium glass cell supplied with laser beams *(photo Michal Parniak, University of Warsaw)*

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https://www.fuw.edu.pl/tl_files/press/images/2025/FUW251016b_fot03.jpg
Rubidium glass cell – miniaturised antenna of the future *(photo Michal Parniak, University of Warsaw)*

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