

Introduction to quantum RF sensors using Rydberg atom technology

Overview of Rydberg sensors

A Rydberg atom sensor is a device that utilises quantum effects to enable the accurate detection and measurement of radio frequency (RF) fields. This is accomplished by enclosing cesium atoms in a small glass bead called a vapour cell. It operates like a receiving antenna, but in contrast to conventional antennas, each individual atom acts like an individual antenna. The Rydberg atom vapour cell exhibits some interesting characteristics that go beyond the capability of conventional antennas, especially at the millimetre wave and higher frequencies, such as 20 GHz to 100+ GHz.

An important characteristic of Rydberg sensors is the fact that they are self-calibrating, which means that they can be used as primary radiated power sensor standards. Another important characteristic is that they are manufactured from strictly dielectric material, namely silicon and glass connected to glass optical fibre. This means that a Rydberg sensor can be introduced into the near-field of a transmitting antenna or placed in very close proximity to radio frequency components such as tuned circuits, only minimally perturbing the electric field. This characteristic makes measurements more accurate, and in some cases can make possible certain measurements having great accuracy that have been previously impossible or impractical using conventional antennas and probes. Because the sensors operate at resonance, they are already more sensitive than standard calibrated antennas in use today.

These two characteristics, self-calibration and minimal electric field perturbation, can be used to solve a number of practical problems, particularly at the millimetre wave frequencies where conducted RF testing is not feasible because of the high degree of cable loss and high sensitivity to a time-varying impedance match due to cable movement. Over-the-Air (OTA) testing is becoming more of the norm for higher operating frequencies, and the use of a Rydberg sensor to measure power output at frequencies like 60 GHz is a reasonable solution. As antennas become more complicated and integrated with transceivers, OTA will be used to test entire systems.

The self-calibrating characteristic of Rydberg sensors is also important in the testing and certification of next-generation wireless devices, which is relatively expensive and time-consuming. This is because conventional RF systems using standard antennas need periodic re-calibration in environments in which robots or people constantly move these devices around.

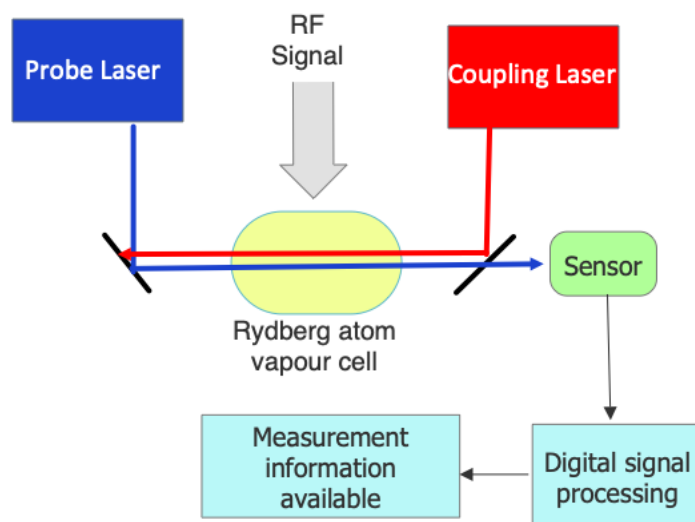


Figure 1: Basic implementation of Rydberg sensor measurement setup: this proof-of-concept fits into a 60 cm X 60 cm X 64 cm miniature component rack in Quantum Valley Ideas Labs optics and electronics lab

Another characteristic that is important in the commercial domain is the fact that these sensors operate extremely well in the millimetre wave frequency range (30 GHz to 300 GHz) and can easily detect RF fields at frequencies well into the terahertz (THz) range. This aspect is important as national regulators and the International Telecommunications Union (ITU) continue to define world-wide radio spectrum allocations at higher and higher frequencies over time.

Arrays of Rydberg sensors can be implemented to accurately construct 3-dimensional maps of electric field images produced by transmitting antennas and other devices, all without any moving parts or metal that can perturb the field. Polarisation and phase information are available, enabling sophisticated mapping of RF field patterns, as well as certain applications such as radar. All data are processed using digital signal processing (DSP) at lower baseband radio frequencies. Experiments have demonstrated imaging of the electric field at $\lambda/650$ resolution, far in the sub-wavelength regime, without interfering with the characterization of the device under test. Furthermore, the technology is 300 times more sensitive, has 70 times better detectable field resolution, and has 300 times better spatial resolution than standard dipole antennas.

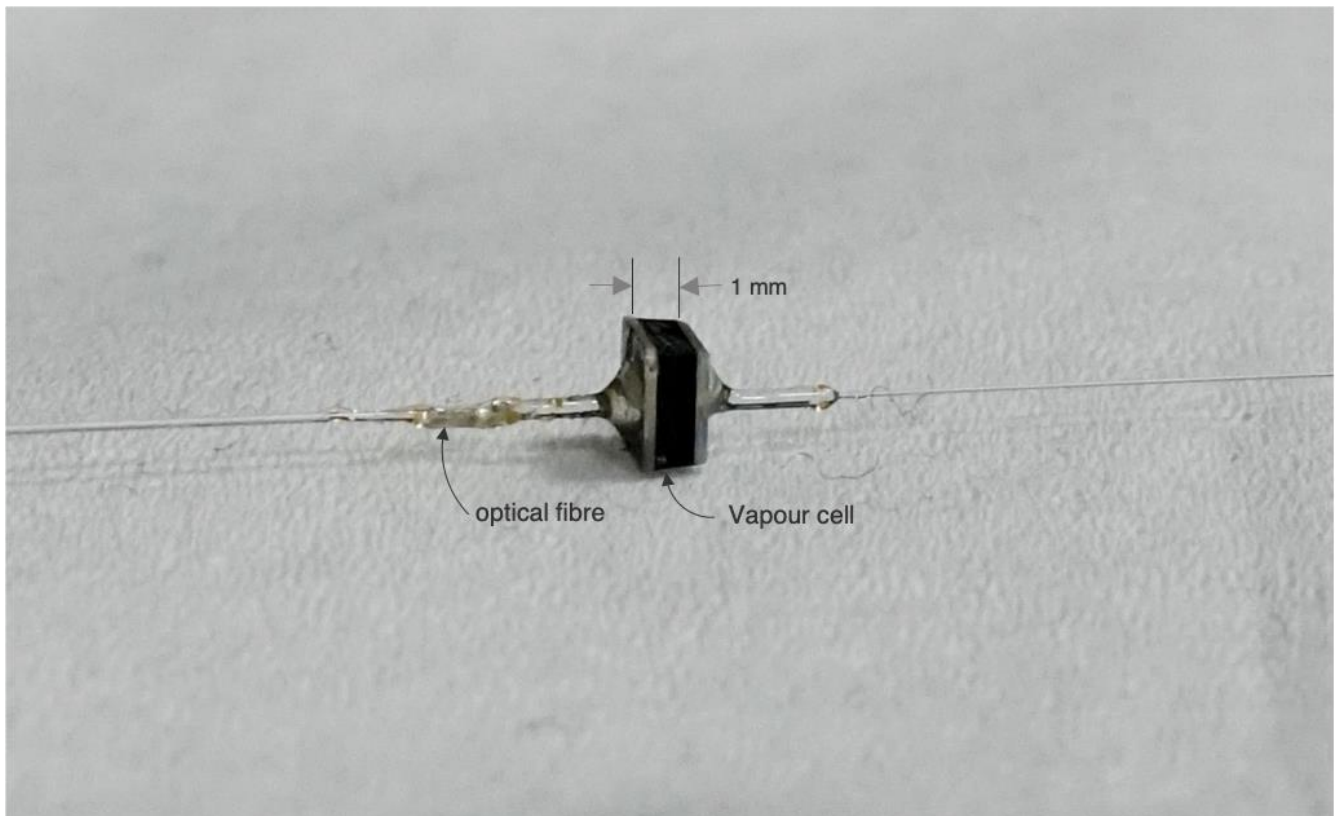


Figure 2: very small quantum RF sensor built at Quantum Valley Ideas Lab in Canada

Rydberg atom sensors can be made extremely small, on the order of 500 microns. Actual implementations by Ideas Lab today are approximately 1 cubic millimetre in volume and are connected to an optical fibre to carry the signals to both excite the Rydberg atoms in the sensor and to carry the information from the sensor to the interface unit and eventually the information display. Because of the optical coupling of signals, the system is fairly well hardened against interference from strong nearby sources of other radio frequency emission.

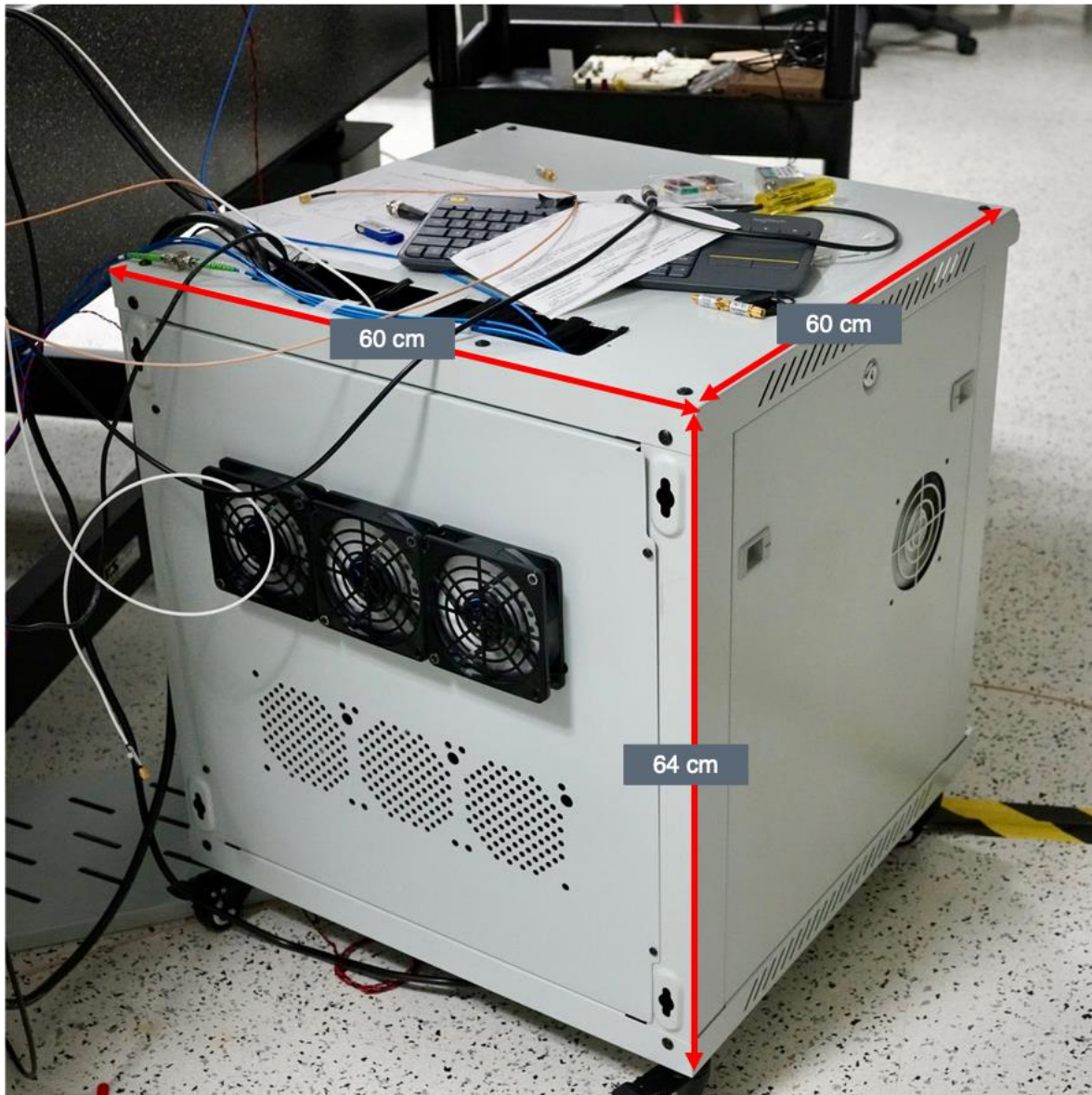


Figure 3 : The proof-of-concept built at Ideas Lab – fairly small compared to the first version

Summary

The implementation of Rydberg atom quantum sensors is an emerging, yet practical method for accurate detection and mapping of radio frequency fields at millimetre wave to Terahertz frequency range. The technology has recently been made practical by discoveries in the areas of vapour-cell implementation, advanced laser control algorithms and digital signal processing of the resulting signals.

A number of practical advantages exist, including the following:

- High sensitivity to RF fields
- Dielectric construction – prevents perturbation of other electric fields
- Optical coupling – resistant to interference from other RF sources
- Ability to resolve phase and polarization of signals
- Super-high spatial resolution – ability to perform high-resolution field mapping

- Self-calibration for given received input power
- Extremely small size possible – less then 1 cubic millimetre volume possible today

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Appendix – a more detailed view

Rydberg atoms are highly-excited atoms of a material, such as cesium, in which one or more electrons would have a very high principal quantum number. The higher this quantum number, the farther the electron(s) would be from the nucleus. This causes Rydberg atoms to have an exaggerated response to electric and magnetic fields, which is the property that allows us to implement RF sensors.

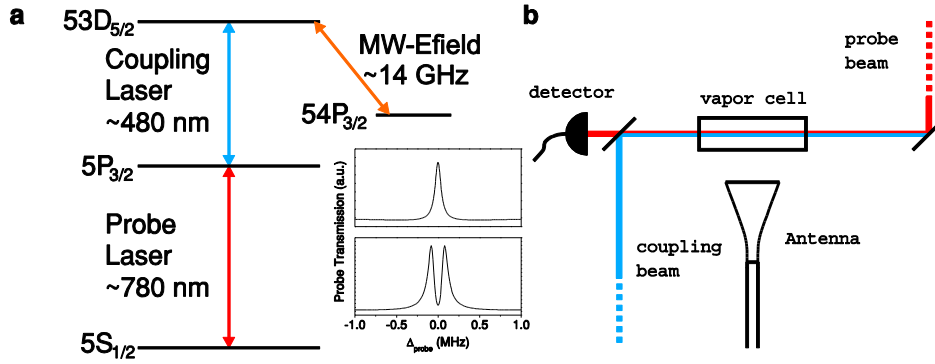


Figure 4 a) Example atomic energy level structure for a measurement using ^{87}Rb . The lasers are all diode lasers. The probe laser transmission in the presence of the coupling laser is recorded. If the RF field is absent, a narrow probe transmission peak is observed as the laser passes through the gas where the probe would normally be absorbed, upper graph in (a).

The Rydberg atom-based quantum detector works by setting up each atom in the sample to function as an interferometer using light, so that the transmission through an atomic sample is sensitive to the applied field. The measurement is proportional to fundamental constants and the properties of the atom, which have been determined by precision, laboratory measurements. This atomic interferometer excites an atomic sample by using coherent light from a laser. This energy from the laser splits the spectrum, producing a measurable output that is proportional to basic physical properties of the atoms being excited. This spectral splitting, $\Delta\nu$, caused by the incident radio frequency radiation of an optically generated quantum interference is ideally proportional to the incident radiation amplitude, E_0 . The proportionality factors only depend on the transition dipole moment, μ_{RF} , of the atomic transition and Planck's constant, h ,

$$E_0 = \frac{h \Delta\nu}{\mu_{RF}},$$

see Figure 4. The atomic gas is contained in a small dielectric cavity which minimally perturbs the incident radiation field.