Overview of Rydberg atom RF sensing

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Purpose and scope: *The purpose of this discussion document is to present a short overview of a very new concept for sensing radio frequency electric fields to people familiar with the problems of RF measurement at microwave frequencies. The scope shall be limited to the domain of radio frequency sensor operation using Rydberg atoms generated within vapour cells using lasers at specific wavelengths.*

Extending the state of the art

The current state of art for detecting radio frequency (RF) information typically incorporates the use of metal, dielectric, or waveguide antennas and/or electric/magnetic field probes to capture the fields of interest. In contrast, we present a completely new way of detecting electric fields that uses the quantum effects of Rydberg atoms excited in glass dielectric vapour cells. Vapour cells are typically small, sealed glass devices filled with a vapour of some sort, such as cesium or rubidium, with lasers coupled by optical fibre. When the vapour cell is in the presence of an RF field, the field is detectable by the way the resonant frequencies of the atoms are perturbed.

While this method may appear in some ways to be a technical substitution for conventional antennas and probes, this is not necessarily the case, as each technology brings something useful to each different domain of usage and frequency range. For example, Rydberg atomic sensors are self-calibrating due to the nature of how the field amplitude is measured. This obviates the traceable calibration that makes conventional reference antennas scarce and expensive. Furthermore, these sensors perform extremely well in frequency ranges well above 20 GHz and into the Terahertz range, where measurement accuracy using conventional techniques tends to diminish.

On the other hand, metal antennas may be a more reasonable choice for lower frequency work in many cases, as the techniques for antenna design in frequencies below 20 GHz are well-known and fairly well developed for most applications. In certain niche applications, where having a small sensor size is advantageous Rydberg atom-based sensors may be a better choice, even below 20 GHz. It is important to understand that although Rydberg RF sensors perform some of the functions of a metal or waveguide antenna, these devices exhibit some very different properties.

Rydberg atoms

Rydberg atoms are highly excited atoms, in which one or more electrons would have a very high principal quantum number [1, 2, 3], which can increase the electron orbital radius from the order of nanometres to microns. The higher this quantum number, the farther the electron(s) would be from the nucleus. Because the electron is weakly bound to the nucleus, Rydberg atoms can have an exaggerated response to electric fields. In fact, the energy levels are so far from their ground state that a Rydberg atom's electron orbit may occupy an area as large as 1 cubic micron. Rydberg atoms can be used as RF

sensors because the electrons can resonantly exchange energy back and forth with an RF electromagnetic field when the electron is so weakly bound to the atom.

Rydberg apparatus in the real world

The reliable creation of Rydberg atoms depends on external excitation, primarily by coherent optical signals. The vapour cell is typically illuminated by two or more lasers of different wavelengths, creating atoms in Rydberg states that have a strong response to an RF field. The RF field is read-out from the response of the atom at optical frequencies. The lasers, signal processing and information display are controlled by a central system controller module which synchronises, and frequency locks the lasers to the atomic resonances appropriate to the desired RF operating frequency band.
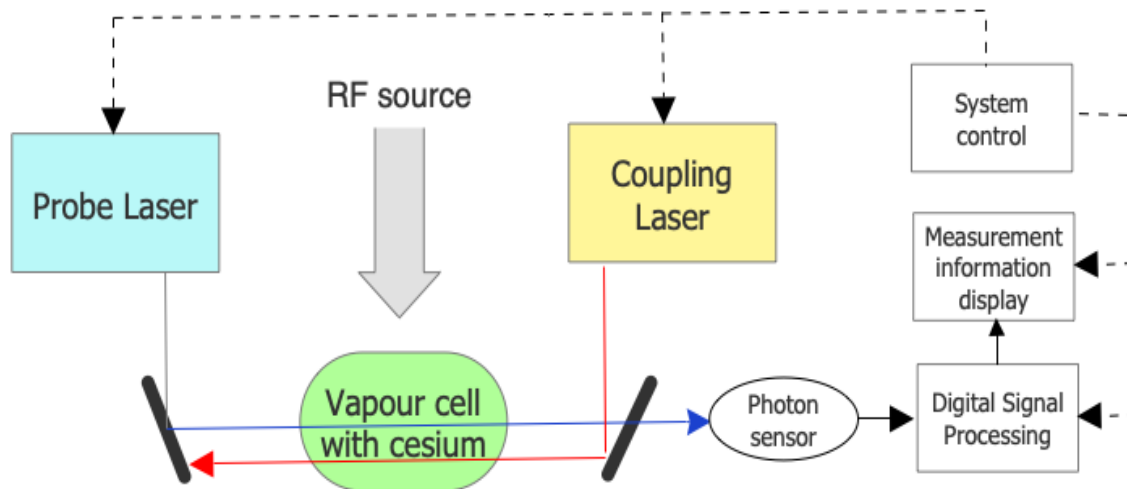

Figure 1: Rydberg RF sensor system architecture

How does it work?

In this example cesium Rydberg atoms are produced by the excitation of the vapour cell by two lasers: 1) one at 852 nm and 2) another at 509 nm in this example. In the presence of RF field energy, Autler-Townes splitting is produced, by which the primary transmission peak at resonance splits into two peaks. The frequency difference between the two peaks is a linear function of the electric field intensity [4,5,6]; the higher the e-field magnitude, the larger the difference in the frequency of the two peaks. The slope of the frequency difference as a function of the electric field amplitude only depends on the properties of the atom, i.e., the transition dipole moment, and Planck's constant, an exact number in the SI system of measurement. The magnitude of the electric field is represented in the frequency domain and is therefore largely immune to amplitude noise components.
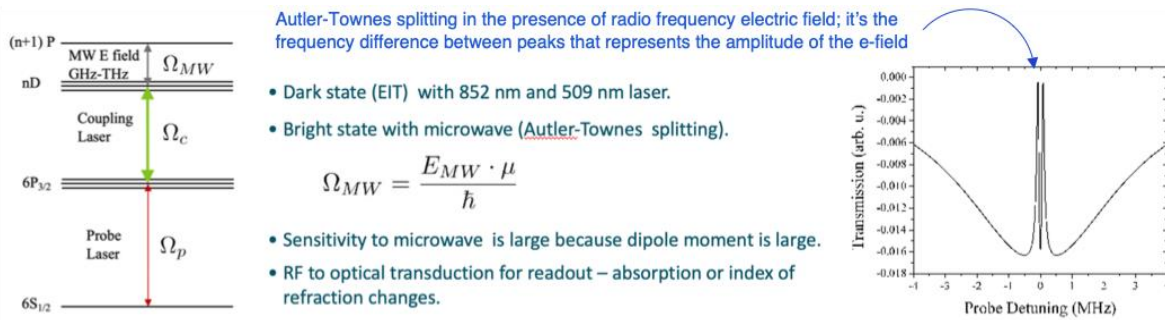
Figure 2: Representation of Rydberg atom energy bands upon excitation from two lasers, [5]

A practical way to map the Autler-Townes frequency splitting to electric field density is as follows:

$$|E| = \Delta f \frac{h}{p}$$

Where:

$|E|$ = electric field density, (v/m)

h = Planck's constant = $6.62607015 \times 10^{-34}$ m² kg / s

p = Electric dipole moment = (charge * distance) = (qd)

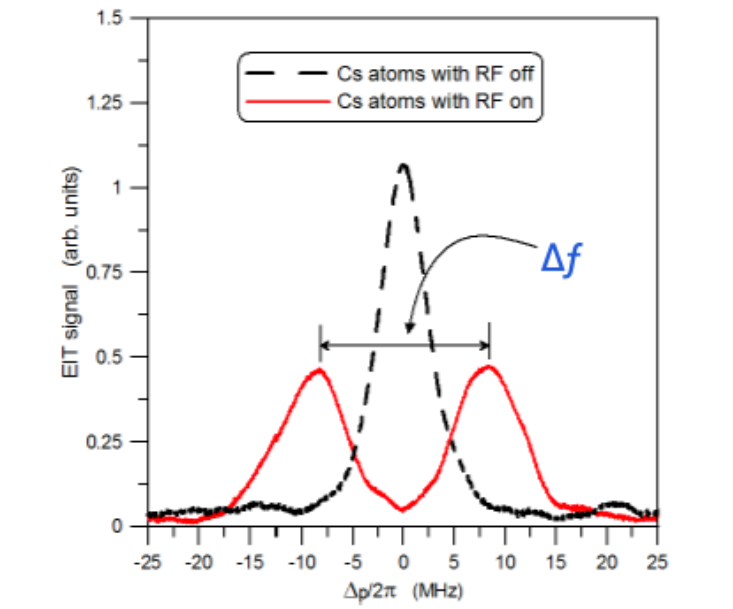Δf = the frequency difference of the two peaks in the frequency domain

Figure : 3A Splitting of the resonant peak upon application of RF, [6]

In many RF applications, it may be desirable to convert the electric field density to an equivalent received power level. This may be done by squaring the field density, dividing it by the free-space impedance of 377Ω and multiplying it by the atomic cross section of the atoms $\left(\frac{3\lambda^2}{2\pi}\right)$, and then converting the resulting power to dBm:

$$P_{watts} = \left(\frac{|E|^2}{377}\right)\left(\frac{3\lambda^2}{2\pi}\right)$$

$$P_{dBm} = 10log_{10}\left(\frac{P}{1 \times 10^{-3}}\right)$$

In this manner, the electric field density measurement can be traced directly to Planck's constant (an SI constant), and the electric dipole moment (invariant once determined) and therefore no local calibration is required.

Potential differentiators and benefits

Some of the useful differentiators include the following:

• Self-calibration for given received input power

• High sensitivity to RF fields: 300 times more sensitive, and 70 times better detectable field resolution, and has 300 times better spatial resolution than standard dipole antennas

• Super-high spatial resolution: imaging of the electric field at λ/650 resolution, far in the sub-wavelength regime, without interfering with the characterisation of the device under test due to the vapour cells' relative electromagnetic transparency

• Ability to construct arrays of vapour cells for special-purpose RF field mapping

• Dielectric construction – reduces perturbation of other electric fields

• Optical coupling – resistant to overload interference from other RF sources

• Ability to resolve phase and polarisation of signals

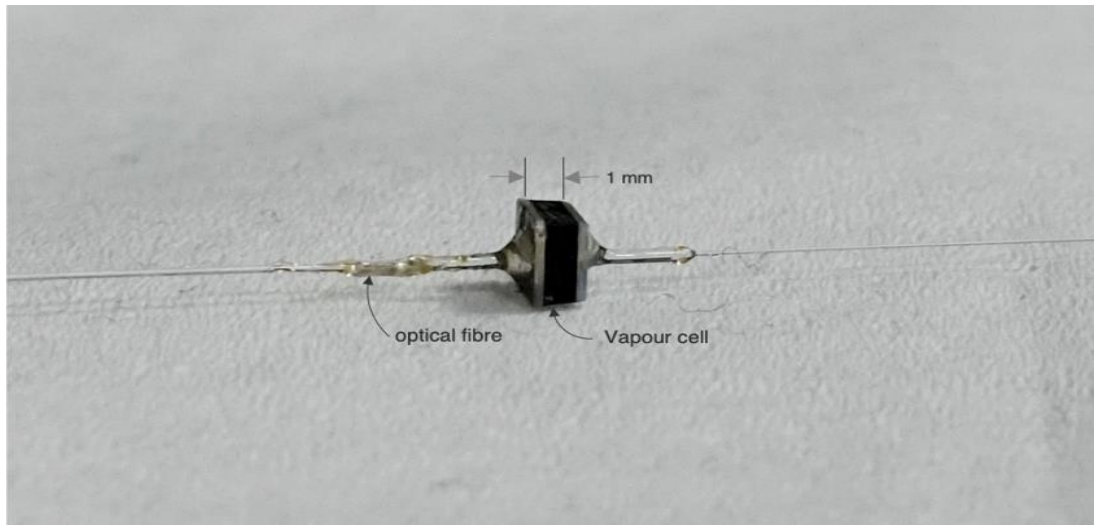• Extremely small size – ~10 cubic millimetre volume possible today - and virtually any shape possible

Figure 4: A small cesium-filled vapour cell coupled to optical fibre on both ends

Conclusions

Quantum sensing of RF electromagnetic fields using Rydberg atoms is still a very new and promising technology for certain applications. Rydberg vapour cell sensing is not a direct technical substitute for "everything radio frequency", but rather works extremely well under certain circumstances that are difficult for conventional antennas, especially at the millimetre wave and higher frequencies where accuracy is important and difficult to achieve by the current state-of-the-art, for example at frequencies of 20 GHz to 100+ GHz. Robust prototype measurement systems exist today, but challenges remain in the areas of laser miniaturisation, laser control, fabrication of vapour cells and digital signal processing. Work is ongoing by several research groups internationally to adapt Rydberg atom vapour cell RF sensing to commercial industrial domains, such as test and measurement systems and specialised radio receivers.

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