Field Enhancement for Sensitivity Improvement of a Room-Temperature Rydberg-Atom Receiver

Georgia Sandidge¹, Gabriel Santamaria Botello #, Zoya Popović #,
¹ Department of Electrical, Computer, and Energy Engineering, The University of Colorado, Boulder, CO 80303, USA

¹Georgia.Sandidge@colorado.edu

Abstract — This paper presents a microwave cavity for sensitivity enhancement in room-temperature Rydberg atom electric field sensors. It can be shown theoretically that without enhancement, such sensors currently do not compete with conventional low-noise amplifier based receivers. We designed a 15 GHz resonator for a specific set of transitions in Rubidium atoms. Owing to its high Q and finesse, the resonator enhances the electric field magnitude sensed by the atoms by a factor \( F \) with respect to an external field coupled through an antenna. The resonator is designed to fit a 4 mm \( \times \) 4 mm \( \times \) 25 mm fused silica vapor cell. The simulated and measured Q-factors are 1900 and 1100, respectively, which corresponds with field enhancement factors of 20 and 14, respectively. The resonator is mechanically tunable over 216 MHz to ensure overlap with the atomic resonance.

Keywords — Electric field measurements, Rydberg atom, waveguide resonant cavity, noise equivalent temperature, noise equivalent field.

I. INTRODUCTION

Recent studies indicate that Rydberg-atom microwave receivers have the potential to achieve higher sensitivity than conventional room-temperature receivers, in principle over a wide range of microwave frequencies from a few 100 MHz to a few THz [1]. The outermost electron of alcali (e.g. Rubidium) atoms in Rydberg states occupies a high energy level, with a large principal quantum number \( n \). For a state \( nLj \), \( L \) refers to the orbital angular momentum or the shape of the energy level, and \( j \) refers to the total angular momentum in that energy level. Our topology targets the intermediate \( 5P_3/2 \) state using a 780.24150 nm probe laser, and then the Rydberg state \( 52D_5/2 \) with a 480.04261 nm coupling laser.

When a probe laser is incident on a vapor of Rubidium atoms in the ground state \( 5S_{1/2} \), the light is fully absorbed by the atoms, and therefore not observed by a photodetector. In a microwave receiver, the excitation of atoms to the Rydberg state is accomplished by using two lasers, as sketched in Fig. 1a. A coupling laser of a precise wavelength excites the atoms to the highly-ionized Rydberg state. When the probe laser at a particular wavelength is incident on the Rydberg atoms, absorption disappears. This is referred to as electromagnetically-induced transparency (EIT), which can be observed by a detector, as illustrated in Fig. 1b showing a transmittance peak of the probe laser.

For detection of an incident RF wave, a useful property of EIT, referred to as Autler-Townes (AT) splitting, is utilized, Fig. 1c. In AT splitting, the presence of an RF signal incident on the vapor cell creates another energy level. This causes the EIT peak measured by the detector to split into two peaks with half magnitude, and with a frequency separation directly correlated to the magnitude of the incident microwave/millimeter-wave field. As an infinite number of energy levels \( n \) exist, a variety of atomic transitions can be targeted with different combinations of laser wavelengths. This allows a narrowband detection scheme that can receive a variety of frequencies, from MHz to THz [4].

This paper is organized as follows. First, we define the sensitivity metric for comparing Rydberg receivers to standard microwave receivers, as the units typically used by the two communities are different. Next, we introduce field enhancement as a motivation to improve Rydberg-atom receivers. A discussion of previously implemented methods is included, and is followed by a description of the resonating waveguide cavity enhancement method developed in this work. Initial measured results are shown, with a discussion of relevant parameters, and estimation on the enhancement factor \( F \) of a Rydberg receiver that the implemented resonator can provide.

II. SENSITIVITY AND FIELD ENHANCEMENT

Rydberg atoms as detectors of both RF electric field magnitude and phase have been demonstrated by many
authors recently, e.g. [5], [3], [6] with a state-of-the-art sensitivity of 1.25 μV/m/√Hz [7] reported at 10.68 GHz. This metric is referred to as the noise-equivalent field (NEF) and is defined as the minimum detectable electric field magnitude per unit square-root of bandwidth. Therefore, establishing a fair comparison between Rydberg receivers and conventional LNA-based microwave receivers can be difficult, as the sensitivity metric of traditional LNA-based microwave receivers is usually the noise figure (NF) or noise equivalent temperature (NET), which is intrinsically a power spectral density.

The gain of the receiving antenna followed by a LNA in a conventional microwave receiver has a significant impact on the electric field sensitivity. To establish a fair comparison, we assume that the receiving antenna is an electrically small dipole, and therefore has a gain $G = 3/2$. A typical commercially-available LNA, such as the Mini-circuit PMA-183PLN+, has a noise figure of 1.3 dB at 10 GHz, corresponding to a noise temperature of about 100 K. Using these values, the minimum electric field that can be resolved in NEF units can be calculated from

$$\text{NEF} = \sqrt{\frac{8\eta_0 \pi k_B T_e}{G \lambda_0^2}},$$

(1)

where $\eta_0$ is the vacuum impedance, $k_B$ the Boltzmann constant, and $\lambda_0$ the free-space wavelength. Ultimately, the sensitivity of the commercially-available LNA corresponds to $\text{NEF} \approx 0.14 \mu$V/m/√Hz, a factor of nearly 10 times better than state-of-the-art Rydberg receiver sensitivities. Other advantageous properties of Rydberg receivers, such as high frequency selectivity, motivate investigation of RF field enhancement methods that can make them competitive with conventional microwave receivers. A few methods have been demonstrated to show enhancement. In [8], a split ring resonator surrounds a small Cesium Rydberg vapor cell at 1.3 GHz, yielding an enhancement factor of $F = 100$, and therefore a sensitivity of $5.5 \mu$V/m/√Hz. Due to its small size, this topology had limited scaling ability to higher frequencies. Alternatively, in [9], a parallel-plate resonator embedded inside a vapor cell for C-band signals demonstrates $F = 16.2$. Although this work does not report the NEF, a 24.2 dB gain in RF field intensity is obtained.

Here we describe a resonant waveguide cavity design for field enhancement at frequencies above X band. For an atomic sensor of $\text{NEF}_0$, one might expect that the sensitivity improves to $\text{NEF}_0/F$ after the addition of field enhancement factor $F$. This would be true for a cavity at absolute zero where quantum noise is negligible. For a room-temperature receiver, thermal noise generated by the lossy resonator has to be taken into account. As shown in [2], a field-enhancing port-fed cavity exhibits an input-referred noise temperature $T_e$ given by

$$T_e = \frac{h f}{k_B} + \frac{Q_c}{Q_i} \left(2 T_p + \frac{h f}{k_B} + \frac{\text{NEF}_0^2}{k_B F^2 \lambda_0^2}\right),$$

(2)

where $Q_i$ and $Q_c$ are the intrinsic and coupling quality factors of the resonator, respectively, $T_p$ is the physical temperature of the resonator, $h$ is the Planck constant, $f$ is the receiver frequency, and

$$A^2 = \frac{8\pi f^2}{\varepsilon_0 c^3 G},$$

(3)

where $\varepsilon_0$ is the vacuum permittivity, $c$ the speed of light and $G$ the antenna gain used to calculate $F$.

From Eq. (2), the effect of cavity temperature on receiver noise temperature is reduced by overcoupling the cavity, $Q_c \ll Q_i$. However, this reduces the field enhancement factor due to impedance mismatch at the input port. Hence, a given set of values $\text{NEF}_0$ and $F$, leads to an optimal ratio $Q_c/Q_i$ that minimizes the noise temperature of the atomic receiver.

**III. FIELD-ENHANCEMENT CAVITY DESIGN**

Referring to Fig. 1, a non-uniform RF field distribution in a Rydberg-atom vapor cell results in multiple Autler-Townes peaks, leading to EIT broadening and sensitivity degradation. Therefore, the resonator is designed to maximize electric field uniformity throughout the volume filled with Rubidium Rydberg atoms. The feed is chosen to be a WR62 rectangular waveguide, which is coupled to the resonator through a small aperture for a 15.096 GHz design frequency. The cavity is composed of three rectangular waveguide sections. Two sections are WR62 waveguides ($A = \lambda_g/4$ long, where $\lambda_g$ is the associated guided wavelength. The third section ($B$) between them is 25 mm long with a transverse cross-section of 6.5 mm × 4.318 mm and operates close to its cutoff frequency where the guided wavelength is large. This makes waveguide B electrically short, with high field uniformity. The fused silica ($\epsilon_e = 3.8$, $\tan \delta = 0.00025$ [10]) vapor cell containing Rubidium atoms is fully enclosed by waveguide B, with a small aperture cut in the top of the resonator to accommodate the tail used for Rb filling. Fig. 2. Laser beam optical windows 2 mm in diameter are manufactured in both sections of waveguide A. This resonator is designed to resonate at a
precise frequency to optimally observe AT splitting; however, manufacturing tolerances (200 \mu m) can result in a frequency shift. A hole is therefore added at the bottom of the resonator for a tuning screw, which can mechanically shift the resonant frequency.

The full-wave simulation (Ansys HFSS) of the resonator with the fused silica vapor cell inserted shows a resonance at 15.0960 GHz with $|S_{11}| = -20.7$ dB. The cavity is designed to be critically coupled, with $Q_i \approx Q_e \approx 1800$. The simulated field enhancement factor is $F \approx 20.4$, assuming the input is coupled to an electrically small antenna with $G = 3/2$. The tuning screw provides a tuning range of 216 MHz, shown in Fig. 3, while the electric field magnitude is given in Fig. 4. The electric field should be linearly co-polarized with the optical field, and for this resonator the polarization extinction ratio is better than 30 dB. The coupling factor is designed by varying the length of the aperture between the WR62 waveguide and waveguide B by 200 \mu m from the nominal value of 5.9 mm, keeping the height constant at 3 mm, with resulting simulated reflection coefficient magnitude and phase shown in Fig. 3.

![Fig. 3. Dependence of reflection coefficient at the WR62 waveguide feed on tuning screw displacement from −0.271 mm to +0.229 mm relative to the position when it is flush with the waveguide B wall. The full tuning range is 216 MHz without significant degradation in Q factor.](image)

![Fig. 4. The magnitude of the electric field in the resonating cavity. Inside the vapor cell, the maximum E-field is 1.18 \cdot 10^5 V/m for a 1 W input power at the waveguide feed. The electric field is linearly polarized with a cross-polarization extinction ratio of 30 dB throughout the vapor cell.](image)

IV. MEASUREMENTS OF RESONATOR

The resonator connected to a 3.5 mm coaxial-to-WR62 waveguide adapter is measured with a PNA with SOLT calibration at the coaxial reference plane (due to the unavailability of WR62 calibration standards). Fig. 6(top) shows the magnitude and phase of the measured reflection coefficient. The baseline off-resonance return loss below 0 dB is due to adapter loss. A resonance is measured at 15.5016 GHz, less than 4% (412 MHz) above the target resonance frequency. Last-minute modifications had to be done to the cavity to accommodate unexpected features in the fused silica vapor cell, namely a bulge in the region where the filling tube attaches to the cell. The cylindrical channel for the filling tube needed to be enlarged near the cavity wall, creating an air pocket that increases the cutoff frequency of the waveguide, thus making it electrically shorter and shifting the resonance to a higher frequency. As shown in Fig. 6(bottom), the reflection coefficient near resonance is normalized in magnitude and phase to 0 dB and 0°, respectively, and fitted with the theoretical reflection coefficient of a single-mode resonator with intrinsic (unloaded) and coupling (external) quality factors $Q_i$ and $Q_e$, respectively:

$$S_{11} = \frac{Q_i - Q_e}{Q_i + Q_e} + j \frac{2Q_i Q_e}{Q_i + Q_e} \left( \frac{f - f_0}{f_0} \right).$$

(4)

From the fitting, we estimate $Q_i \approx 1100$ and $Q_e \approx 2860$. We attribute the strongly undercoupled behavior of the cavity to extra losses arising from the drilling modifications.

![Fig. 5. Simulated reflection coefficient magnitude and phase vs. frequency for three lengths of a 3-mm tall aperture: nominal length of 5.9 mm ±200 \mu m. The mode changes from undercoupled to overcoupled as the aperture increases.](image)

![Fig. 6. (Top) Magnitude and phase of measured reflection coefficient showing a resonance at 15.5016 GHz. (Bottom) Inset of the resonance shown in the top figure, and theoretical fit (dashed) curves.](image)
Using the experimentally measured $Q_i$ along with Eq. (2), the noise temperature of an atomic receiver enhanced with the manufactured cavity is estimated in Fig. 7 as a function of the intrinsic (not-enhanced) atomic sensitivity $\text{NEF}_0$. The noise temperature results are compared to the best reported values for an LNA in the 14 GHz to 16 GHz range, $T_{\text{LNA}} \approx 83.6$ K [11], [12]. For each case, the results are also compared with the equivalent noise temperature of the atomic receiver without the enhancement cavity. The cavity-enhanced atomic receiver is competitive to LNAs for intrinsic sensitivity values better than $\text{NEF}_0 \approx 1 \mu V m^{-1} Hz^{-1/2}$. In this case, the minimum noise temperature $T_e \approx 110$ K is achieved for a significantly overcoupled cavity where $Q_i/Q_c \approx 13.8$. Note that without the cavity, the atomic receiver exhibits a noise temperature $T_e \approx 4160$ K. Therefore, despite exhibiting half of the designed intrinsic $Q$, the manufactured cavity can significantly improve the noise performance of a non-enhanced Rydberg receiver. This would require enlarging the coupling aperture so that the undercoupled mode becomes overcoupled.

![Fig. 7. Estimated noise temperature of manufactured cavity as a function of the coupling strength, for different $\text{NEF}_0$ values.](image)

**V. CONCLUSIONS**

In summary, this paper presents the design and characterization of a Ku-band metallic waveguide cavity with an internal fused silica vapor cell for sensitivity enhancement of a room-temperature Rydberg atom electric field sensor, designed for a Rubidium 52D$_{5/2}$ transition. The resonator is designed to have a high field uniformity for a linearly-polarized mode, and is tunable to account for manufacturing tolerances. Post-manufacturing modifications to the microwave cavity had to be done to accommodate unexpected geometric features of the vapor cell, degrading the intrinsic $Q$, and reducing the field enhancement factor from 20 to 14. Despite this, the cavity can provide more than one order of magnitude of sensitivity improvement with respect to non-enhanced atomic sensors.

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**REFERENCES**


