REPORT DOCUMENTATION PAGE

Form Approved OMB NO. 0704-0188

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From - To)
21-05-2017	Final Report	1-Jul-2011 - 28-Feb-2018

4. TITLE AND SUBTITLE
Final Report: A Rydberg Atom Electric Field Sensor

5a. CONTRACT NUMBER
W911NF-11-1-0179

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
0D10BM

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

6. AUTHORS
James P. Shaffer

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES
University of Oklahoma
201 Stephenson Parkway
Five Partners Place, Suite 3100
Norman, OK 73019 -9705

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS (ES)
U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSOR/MONITOR'S ACRONYM(S)
ARO

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
60181-PH-DRP.24

12. DISTRIBUTION AVAILIBILITY STATEMENT
Approved for Public Release; Distribution Unlimited

13. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT
The overarching goal of this work was to demonstrate the advantages and possibilities of Rydberg atom-based sensors for radio-frequency electric fields. By exploiting the exaggerated and tunable properties of highly excited Rydberg atoms and Rydberg atom electromagnetically induced transparency (EIT), we were able to show that Rydberg atoms can be used as absolute, self-calibrated sensors for radio-frequency electric fields in the 1-1000 GHz regime. Our results were obtained with systems that can conform to compact, portable packages based on thermal vapor cells. We demonstrated that Rydberg atom-based sensors are the most accurate and sensitive absolute

15. SUBJECT TERMS
Atom-based sensing, Rydberg atoms, Radio Frequency fields

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
UU	UU	UU	UU		James Shaffer
					19b. TELEPHONE NUMBER 405-325-6961

Standard Form 298 (Rev 8/98)
Prescribed by ANSI Std. Z39.18

Report Title

Final Report: A Rydberg Atom Electric Field Sensor

ABSTRACT

The overarching goal of this work was to demonstrate the advantages and possibilities of Rydberg atom-based sensors for radio-frequency electric fields. By exploiting the exaggerated and tunable properties of highly excited Rydberg atoms and Rydberg atom electromagnetically induced transparency (EIT), we were able to show that Rydberg atoms can be used as absolute, self-calibrated sensors for radio-frequency electric fields in the 1-1000 GHz regime. Our results were obtained with systems that can conform to compact, portable packages based on thermal vapor cells. We demonstrated that Rydberg atom-based sensors are the most accurate and sensitive absolute sensors for radio frequency electric fields yet developed and the only ones that can be used for frequencies above ~100 GHz. We showed that our approach can be used for near field imaging and vector detection of radio frequency electric fields. We also showed that the sensitivity of the sensor is limited by photon shot noise on the probe laser detector. We reported on the ultimate limitations of the sensor. In addition, we investigated the effect that the vapor cell has on the detected field and the effect of the walls on the Rydberg atoms.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received		Paper
01/18/2013	1	R. Ritter, R. Daschner, H. Kübler, N. Frühauf, E. Kurz, R. Löw, T. Pfau. Fabrication and characterization of an electrically contacted vapor cell, Optics Letters, (06 2012): 2271. doi: 10.1364/OL.37.002271 292,034.00
01/18/2013	5	Arne Schwettmann, Jonathon Sedlacek, James P. Shaffer. Field-programmable gate array based locking circuit for external cavity diode laser frequency stabilization, Review of Scientific Instruments, (10 2011): 103103. doi: 10.1063/1.3646477 292,038.00
01/18/2013	3	Jonathon A. Sedlacek, Arne Schwettmann, Harald Kübler, Robert Löw, Tilman Pfau, James P. Shaffer. Microwave electrometry with Rydberg atoms in a vapour cell using bright atomic resonances, Nature Physics, (09 2012): 819. doi: 10.1038/nphys2423 292,036.00
05/17/2015	4	James P. Shaffer. Atom optics: Marriage of atoms and plasmons, Nature Photonics, (07 2011): 451. doi: 10.1038/nphoton.2011.174 292,037.00
05/21/2017	7	J. Sedlacek, A. Schwettmann, H. Kuebler and J.P. Shaffer. Atom-Based Vector Microwave Electrometry Using Rubidium Rydberg Atoms in a Vapor Cell, Physical Review Letters, (08 2013): 63001. doi: 10.1103/PhysRevLett.111.063001 334,149.00
05/21/2017	23	Santosh Kumar, Haoquan Fan, Harald Kübler, Akbar J. Jahangiri, James P. Shaffer. Rydberg-atom based radio-frequency electrometry using frequency modulation spectroscopy in room temperature vapor cells, Optics Express, ( ): 8625. doi: 1,041,596.00
05/21/2017	22	Santosh Kumar, Haoquan Fan, Harald Kübler, Jiteng Sheng, James P. Shaffer. Atom-Based Sensing of Weak Radio Frequency Electric Fields Using Homodyne Readout, Scientific Reports, ( ): 42981. doi: 1,041,595.00
05/21/2017	8	H. Fan, S. Kumar, H. Kubler, R. Daschner and J.P. Shaffer. Subwavelength microwave electric-field imaging using Rydberg atoms inside atomic vapor cells, Optics Letters, (05 2014): 3030. doi: 10.1364/OL.39.003030 334,180.00
05/21/2017	9	J. P. Shaffer and L.G. Marcassa. Interactions in Ultracold Rydberg Gases, Advances in Atomic, Molecular and Optical Physics, (06 2014): 47. doi: 334,181.00
05/21/2017	10	," A. Urvoy, F. Ripka, I. Lesanovsky, D. Booth, J.P. Shaffer, T. Pfau and R. Low. Strongly correlated growth of Rydberg aggregates in a vapor cell, P H Y S I C A L R E V I EW L E T T E R S, (08 2014): 203002. doi: 334,182.00
05/21/2017	11	H.Q. Fan, S. Kumar, H. Kubler, S. Karimkashi and J.P. Shaffer. Atom based RF electric field sensing, Journal of Physics B: Atomic Molecular Optical Physics, (05 2015): 202001. doi: 367,790.00
05/21/2017	12	H.Q. Fan, S. Kumar, C. Holloway, J. Gordon and J.P. Shaffer. Effect of Vapor Cell Geometry on Rydberg Atom-based Radio-frequency ElectricField Measurements, PHYSICAL REVIEW Applied, (07 2015): 0044015. doi: 367,791.00
09/05/2016	15	Yuanxi Chao, Jiteng Sheng, Jonathon A. Sedlacek, James P. Shaffer. Surface phonon polaritons on anisotropic piezoelectric superlattices, Physical Review B, ( ): . doi: 1,017,323.00

09/05/2016	17	H Q Fan, S Kumar, H Kübler, J P Shaffer. Dispersive radio frequency electrometry using Rydberg atoms in a prism-shaped atomic vapor cell, Journal of Physics B: Atomic, Molecular and Optical Physics, ( ): 104004. doi: 1,017,325.00
09/05/2016	16	J.?A. Sedlacek, E. Kim, S.?T. Rittenhouse, P.?F. Weck, H.?R. Sadeghpour, J.?P. Shaffer. Electric Field Cancellation on Quartz by Rb Adsorbate-Induced Negative Electron Affinity, Physical Review Letters, ( ): . doi: 1,017,324.00
09/06/2015	13	F. Ripka, A. Urvoy, I. Lesanovsky, D. Booth, J.?P. Shaffer, T. Pfau, R. Löw. Strongly Correlated Growth of Rydberg Aggregates in a Vapor Cell, Physical Review Letters, (05 2015): 0. doi: 10.1103/PhysRevLett.114.203002 367,792.00
09/06/2015	14	Luis Marcassa, James P. Shaffer. Interactions in Ultracold RydbergGases, Advancesin Atomic Molecular and Optical Physics, (08 2014): 47. doi: 367,793.00
TOTAL:	**17**	

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received	Paper
TOTAL:	

Number of Papers published in non peer-reviewed journals:

(c) Presentations

1. “Generation of 480 nm CW Light for Rydberg Excitation of Rb,” J. Sedlacek, A. Schwettmann, and J.P. Shaffer, DAMOP, Atlanta (2011).

2. “Probing RF Electric Fields with Rydberg Atoms,” A. Schwettmann, J. Sedlacek, C. Gentry, and J.P. Shaffer, DAMOP, Atlanta (2011).

3. “Coherent Rydberg Excitation in Thermal Microcells,” R. Low, R. Daschner, H. Kubler, B. Huber, T. Baluktsian, A. Koelle, J.P. Shaffer and T. Pfau, DAMOP, Atlanta (2011). (invited)

4. “A Rydberg Atom Electric Field Sensor,” J.P. Shaffer, DARPA Quasar and Orchid Meeting, San Diego, CA (2011). (invited)

5. “Probing RF Electric Fields with Rydberg Atoms,” A. Schwettmann, J. Sedlacek, C. Gentry, H. Kuebler and J.P. Shaffer, DARPA Quasar and Orchid Meeting, San Diego, CA (2011).

6. “A Rydberg Atom Electric Field Sensor,” J.P. Shaffer, DARPA Quantum Assisted Sensing-Fields, Cambridge, MA (2012). (invited)

7. “Quantum Assisted Sensing Using Rydberg Atom Electromagnetically Induced Transparency,” J. Sedlacek, H. Fan, A. Schwettmann, H. Kubler, T. Pfau, and J.P. Shaffer, DAMOP, Los Angeles, CA (2012).

8. “Polarization Dependent Dark Resonances in Electromagnetically Induced Transparency with Rydberg Atoms,” J. Sedlacek, A. Schwettmann, H. Fan and J.P. Shaffer, DAMOP, Los Angeles, CA (2012).

9. “Quantum Assisted Sensing Using Rydberg Atom Electromagnetically Induced Transparency,” J.P. Shaffer, DARPA-Quasar Review, Santa Barbara, CA (2012).

10. “Vector Electrometry Using Rydberg Atom Electromagnetically Induced Transparency,” J. Sedlacek, H. Kubler, and J.P. Shaffer, DAMOP, Quebec City, Quebec, Canada (2013).

11. “Using Rydberg Atom Electromagnetically Induced Transparency for Microwave Electrometry Applications,” J. Sedlacek, H. Fan, R. Daschner, C. Ewel, H. Kubler and J.P. Shaffer, DAMOP, Quebec City, Quebec, Canada (2013).

12. “Quantum Assisted Sensing Using Rydberg Atom Electromagnetically Induced Transparency,” J.P. Shaffer, DARPA-Quasar Review, Santa Cruz, CA (2013).

13. “Quantum Assisted Sensing Using Rydberg Atom Electromagnetically Induced Transparency,” J.P. Shaffer, DARPA-Quasar Review, Long Beach, CA (2014).

14. "Quantum Assisted Electrometry using Electromagnetically Induced Transparency with Rydberg Atoms in a Vapor Cell," H.Q. Fan, S. Kumar, R. Daschner, H. Kubler, J. Sedlacek and J.P. Shaffer, DAMOP, Madison WI (2014).

15. "Sub-wavelength Microwave Electric Field Imaging using Rydberg Atoms," H.Q. Fan, S. Kumar, R. Daschner, H. Kubler, and J.P. Shaffer, DAMOP, Madison WI (2014).

16. "Probing Atom Surface Interactions Using Rb Rydberg Atoms," J. Sedlacek, H. Kubler, C. Ewel and J.P. Shaffer, DAMOP, Madison WI (2014).

17. “Quantum Assisted Sensing Using Rydberg Atom Electromagnetically Induced Transparency,” J.P. Shaffer, DARPA-Quasar Review, Boulder, CO (2014).

18. “Using Rubidium Rydberg Atoms to Probe Atom-Surface Interactions,” J. Sedlacek and J.P Shaffer, 2nd International Conference on Rydberg Atom Physics, Recife, Brazil (2014).

19. “Coherent Control of Strongly Interacting Rydberg Gases in Thermal Vapor Cells,” H. Kubler, R. Low, J.P. Shaffer and T. Pfau, 2nd International Conference on Rydberg Atom Physics, Recife, Brazil (2014). (invited)

20. “Cs Trilobite Molecules and Rydberg Atom Interactions,” D. Booth, J. Yang and J.P. Shaffer, 2nd International Conference on Rydberg Atom Physics, Recife, Brazil (2014).

21. “Production of a 2-D Electron Gas Using Rydberg Atoms and Surface Adsorbates,” J.P. Shaffer, B2 conference on Quantum Hybrid Systems, Tucson, AZ (2015). (invited)

22. “Quantum Assisted Sensing Using Rydberg Atom Electrometry,” J.P. Shaffer, DARPA-QUASAR Review, Boston, MA (2015).

23. “Atom-surface Studies with Rb Rydberg Atoms,” Y. Chao, J. Sheng, J. Sedlacek and J.P. Shaffer, DAMOP, Columbus, OH (2015).

24. “Homodyne Microwave Electric Field Measurements Using Cs Rydberg Atoms in Vapor Cells,” H. Fan, S. Kumar and J.P. Shaffer, DAMOP, Columbus, OH (2015).

25. “Neutralization of Rb Surface Adsorbate Electric Fields by Slow Electron Attachment,” J. Sedlacek, G. Chao and J.P. Shaffer, DAMOP, Columbus, OH (2015).

26. “Quantum Assisted Sensing Using Rydberg Atom Electrometry,” J.P. Shaffer, DARPA-QUASAR Review, Santa Barbara, CA (2015).

27. “Electric field cancellation on quartz by Rb adsorbate-induced negative electron affinity,” J.P. Shaffer, DAMOP, Providence, RI (2016). (invited)

28. “Electromagnetically induced transparency with Rydberg atoms inside a high-finesse optical cavity,” J. Sheng, S. Kumar, J. Sedlacek, Y. Chao, H. Fan and J.P. Shaffer, DAMOP, Providence, RI (2016).

29. “Radio-frequency Electrometry Using Rydberg Atoms in Vapor Cells: Towards the Shot Noise Limit,” S. Kumar, H. Fan, A. Jahangiri, H. Kubler, and J.P. Shaffer, DAMOP, Providence, RI (2016).

30. “Electric field cancellation on quartz by Rb adsorbate-induced negative electron affinity,” J.P. Shaffer, Correlation and Order in Rydberg Gases, Lorentz Center, Leiden, Netherlands (2016). (invited)

31. “Electric field cancellation on quartz by Rb adsorbate-induced negative electron affinity,” J.P. Shaffer, LAOP, Medellin, Colombia (2016). (invited)

32. “Quantum Assisted Sensing Using Rydberg Atom Electrometry,” J.P. Shaffer, DARPA-QUASAR Review, Arlington, VA (2016).

33. “Microwave electric field measurement using frequency modulation spectroscopy in Rydberg atoms vapor cells,” S. Kumar, H. Fan, A. Jozani, H. Kübler, and J.P. Shaffer, The International Conference on Fiber Optics and Photonics (PHOTONICS 2016), Kanpur, India (2016).

34. “Weak microwave electric field measurement using Rydberg atoms in vapor cells,” S. Kumar, H. Fan, A. Jozani, H. Kübler, and J.P. Shaffer, DAE-BRNS National Laser Symposium (NLS-25) KIIT University, Bhubaneswar, India (2016).

35. “Rb adsorbate-induced negative electron affinity on quartz,” J. A. Sedlacek, E. Kim, S. T. Rittenhouse, P. F. Weck, H. R. Sadeghpour, and J. P. Shaffer, ICPEAC, Queensland, Australia (2017).

36. “Sensitivity limits of Rydberg atom-based radio frequency electric field sensing,” A. Jahangiri, S. Kumar, H. Kubler, H. Fan and J.P. Shaffer, DAMOP, Sacramento, CA (2017).

37. “Photon shot noise limited radio frequency electric field sensing using Rydberg Aatoms in vapor cells,” S. Kumar, A. Jahangiri, H. Fan, H. Kubler and J.P. Shaffer, DAMOP, Sacramento, CA (2017).

38. “Quantum signal transduction using Rydberg atoms,” Y. Chao and J.P. Shaffer, Second International Conference on Rydberg Atoms and Molecules, Taiyuan, China (2017). (invited)

Number of Presentations: 38.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

09/06/2016 18 Christopher L. Holloway , Joshua A. Gordon , Haoquan Fan , Santosh Kumar , and James P. Shaffer. The uncertainties associated with Rydberg atom based electric field measurements,
2015 USNC-URSI Radio Science Meeting (Joint with AP-S Symposium). 19-JUL-15, Vancouver, BC, Canada. : ,

09/06/2016 19 C. L. Holloway, J. A. Gordon, M. T. Simons, H. Fan, S. Kumar, J. P. Shaffer, D. A Anderson, A. Schwarzkopf, S. A. Miller, N. Thaicharoen and G. Raithel. Atom-based RF electric field measurements: An initial investigation of the measurement uncertainties,
2015 IEEE International Symposium on Electromagnetic Compatibility - EMC 2015. 16-AUG-15, Dresden, Germany. : ,

TOTAL: **2**

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

09/05/2016 6.00 D. Barredo, H. Kubler, J.P. Shaffer, T. Baluktsian, H. Giessen, R. Low and T. Pfau. Coherent Rydberg excitationin microscopic thermal vapor cells,
20th International Conference on Laser Spectroscopy. 29-MAY-11, Hannover, Germany. : ,

TOTAL: **1**

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received Paper

TOTAL:

Number of Manuscripts:

Books

Received	Book

TOTAL:

Received	Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

1. Ted and Cuba Webb Presidential Professor 2013-present
2. Homer L. Dodge Professor of Atomic, Molecular and Optical Physics 2014 – present
3. Carl T. Bush Lecturer
4. US (APS)-Brazil (SBF) Professorship -2015-2016
5. Oklahoma State Regents Award for Superior Research and Creative Activity 2016

Graduate Students

NAME	PERCENT_SUPPORTED	DISCIPLINE
John Sedlacek	100	
Haoquan Fan	100	
Akbar Jahangiri	25	
Renate Daschner	50	
FTE Equivalent:	**2.75**	
Total Number:	**4**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
Harald Kuebler	1.00
Santosh Kumar	0.00
Jiteng Sheng	0.00
FTE Equivalent:	**1.00**
Total Number:	**3**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
James Shaffer	0.08	
Tilman Pfau	0.00	
FTE Equivalent:	**0.08**	
Total Number:	**2**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED	DISCIPLINE
Matt Banks	0	Physics
Anshul Vakaria	0	Physics
Peter Tower	0	Physics
Soumya Kanungo	0	Physics
Jon Kunjummen	0	Physics
FTE Equivalent:	**0.00**	
Total Number:	**5**	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 4.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 5.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 3.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 3.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields: 2.00

Names of Personnel receiving masters degrees

NAME	
Jon Sedalacek	
Haoquan Fan	
Total Number:	**2**

Names of personnel receiving PHDs

NAME	
Jon Sedlacek	
Haoquan Fan	
Total Number:	**2**

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

See Attachment

Technology Transfer

We worked on an phase I SBIR associated with this work with Cold Quanta. Three other companies also worked on Phase I SBIRs. A new company, Rydberg Technology formed as a result of this work. In addition, the PI gave a talk at Honeywell in Plymouth, MN on starting a joint project. NIST also started a project associated with this research and we worked with them on several joint papers. We sent some of our codes to the Army Research Labs.

A Rydberg Atom Electric Field Sensor

W911NF1110179 – 60181PHDRP

James P. Shaffer
The Homer L. Dodge Department of Physics and Astronomy,
The University of Oklahoma, 440 W. Brooks St., Norman OK 73019

Forward: The overarching goal of this work was to demonstrate the advantages and possibilities of Rydberg atom-based sensors for radio-frequency electric fields. By exploiting the exaggerated and tunable properties of highly excited Rydberg atoms and Rydberg atom electromagnetically induced transparency (EIT), we were able to show that Rydberg atoms can be used as absolute, self-calibrated sensors for radio-frequency electric fields in the 1-1000 GHz regime. Our results were obtained with systems that can conform to compact, portable packages based on thermal vapor cells. We demonstrated that Rydberg atom-based sensors are the most accurate and sensitive absolute sensors for radio frequency electric fields yet developed and the only ones that can be used for frequencies above ~100 GHz. We showed that our approach can be used for near field imaging and vector detection of radio frequency electric fields. We also showed that the sensitivity of the sensor is limited by photon shot noise on the probe laser detector. We reported on the ultimate limitations of the sensor. In addition, we investigated the effect that the vapor cell has on the detected field and the effect of the walls on the Rydberg atoms.

Table of Contents:

I. Statement of Problem Studied: For this grant, we studied the use of Rydberg atoms for absolute, self-calibrated radio-frequency electric field sensing. We measured detection sensitivities, the possibility of vector detection, and imaging of radio-frequency electric fields. We studied the limitations and optimization of the method, including the effects of the vapor cell.

<u>II. Summary of Most Important Results:</u> We showed during the period of this project that atoms can be used to accurately measure radio frequency electric fields [1]. EIT is used to readout the effect of a radio frequency electric field on atoms contained in a vapor cell at room temperature, acting as an radio to optical frequency transducer [2, 3]. The possibility of performing high resolution Rydberg atom spectroscopy in micron sized vapor cells is an important enabler of the method [4, 5], particularly at higher radio frequencies. The Rydberg atom-based radio frequency electric field measurement is promising for performing traceable measurements with a higher sensitivity, accuracy and stability than conventional antenna-based standards. There are a number of applications for which Rydberg atom electric field sensing holds considerable promise, because of its accuracy, sensitivity, and dielectric construction. Rydberg atom-based radio frequency electrometry has widespread applications in areas such as antenna calibration, antenna validation and design, signal detection, terahertz sensing and the characterization of electronics and materials in the radio frequency part of the spectrum.

Rydberg atom electrometry uses light fields to set up each atom in a thermal vapor as an interferometer whose optical response is perturbed in a known way by an incident microwave field resonantly interacting via a Rydberg transition. The measurement of the electric field is then linked to the properties of the atom, which can be established through precision measurements carried out in specialized labs, and physical constants. The current sensitivity of Rydberg atom-based radio frequency electric field sensing that was set during the performance period of this project by us is ~3 $\mu V\ cm^{-1} \cdot Hz^{-1/2}$ [1]. Imaging [6-8] and vector detection [9] were also demonstrated by our group first and validated by others. The high sensitivity of Rydberg atom-based radio frequency electric field measurement is the result of the large transition dipole moments between Rydberg states, 100-10000 ea_0 depending on the transition [10]. The shot noise, or projection noise, limited sensitivity of a collection of atoms in a vapor cell is several orders of magnitude higher, ~3, than what has been realized so far, depending on the frequency and other parameters, such as vapor cell gas density [2]. The sensor is currently limited by photon shot noise from the EIT probe laser that is present in the detection process [11-12].

<u>Key Findings:</u>

a. ***Demonstration of Method*:** In ref. [1], we demonstrated the basic method for measuring radio frequency electric fields using akali atoms contained in a thermal vapor cell based on EIT. In this work, we were able to show that we could achieve sensitivities of 30 $\mu V\ cm^{-1}\ Hz^{-1/2}$ and accuracies of ~1%. We investigated two different regimes. In the first regime, the Autler-Townes splitting due to the interaction of radio frequency electric field was measured directly. In the low radio frequency electric field regime, we showed that the radio frequency electric field could be determined using the amplitude of the EIT transmission peak. Basic limitations and external perturbations were outlined. How to use the method in both the Autler-Townes regime and in the transmission amplitude detection regime were described. Ref. [1] is the seminal paper in the field upon which all other works have been based.

b. ***Demonstration of Vector Electrometry***: In ref. [9] we showed that one could use the hyperfine sub-states of the EIT system to determine the vector direction of the RF electric field. In this approach, optical pumping is used to create two different systems within the atom. One system is a four-level EIT level structure and the other system is a three-level EIT structure. The vector orientation of the RF electric field can be determined by examining how much signal comes from the three-level vs. the four-level system. An angular resolution of ~0.5 degrees was shown in the report. The sensitivities and accuracies were comparable to those found in ref. [1].

c. ***Demonstration of Sub-Wavelength Imaging***: During the course of this project we also demonstrated sub-wavelength radio frequency electric field imaging. We achieved $\lambda/650$ above a strip line and in a vapor cell inserted into a radio frequency electric field standing wave. The accuracy and sensitivities obtained were similar to ref. [1]. The resolution of the method was set by the imaging apparatus used for the experiments, namely the spatial resolution of the imaging system.

d. ***Analysis of the Fundamental Limitations of the Method***: In ref. [2], we analyzed the Rydberg atom-based sensor and determined some of the fundamental limitations affecting the ultimate sensitivity. These were the number of atoms participating and the integration time for the measurement. The major constraints influencing the interaction time were collisions between the atoms in the vapor cell, particularly atoms in Rydberg states [13], and the natural lifetime of the Rydberg states. We also addressed transit time broadening and wall collisions. The number of participating atoms is affected by the collision rates and transit time broadening, through the laser beam sizes. Ultimately, we found that the projection noise limit (limit set by the atomic sample), depending on state and parameters, such as density, can be in the pV cm^{-1} $Hz^{-1/2}$ range. The accuracy is determined by the knowledge of atomic structure, particularly the transition dipole moments. The accuracy of the transition dipole moments are currently ~ 1%, although this is a conservative figure. The vapor cell can affect the accuracy as well since there is some scattering of the incident radio frequency electric field, but this can be limited by choosing a small vapor cell size compared to the wavelength of the radio frequency radiation. The vapor cell can be made so as to enable an accuracy of better than 1% depending on the size and composition of the vapor cell. The Doppler mismatch between the coupling and probe lasers needed for the two-photon EIT process was also addressed.

e. ***Interferometric Read-Out:*** We used a Mach-Zehnder interferometer to increase the signal to noise ratio of the probe read-out [11]. Using the interferometric setup, we increased the sensitivity in anticipation of having to utilize smaller vapor cells (less optical depth). We achieved a sensitivity of 3 μV cm^{-1} $Hz^{-1/2}$. More importantly, in this work, the optimized signal was photon shot noise limited. This observation is important because the probe laser power is limited by the desire to decrease collision rates due to Rydberg atom collisions as described in ref. [2].

f. ***Frequency Modulated Read-Out:*** In order to achieve better signal to noise ratio, we used stabilized frequency modulated (FM) spectroscopy to reach the photon shot noise limited sensitivity [12]. Using FM spectroscopy, we achieved a sensitivity limit of ~5 μV cm^{-1} $Hz^{-1/2}$. These results are similar to those we have obtained using the homodyne, interferometric technique described in (5.), because we also reached the photon shot noise limit of the probe laser detection [11]. The homodyne and FM measurements mutually support this conclusion. We also proposed a new read-out scheme that, in principle, can achieve better spectral resolution, ~kHz, by using the Cs $6S_{1/2} \leftrightarrow 6P_{1/2} \leftrightarrow 9S_{1/2} \leftrightarrow$ nl three-photon transition for readout. This three photon process cancels out residual Doppler shifts that limit the spectral resolution to ~1.7 MHz for the two photon readout [1]. The three photon readout has the potential to improve the sensitivity and accuracy of the method by expanding the Autler-Townes regime. For the three photon readout, we theoretically analyzed the technique and showed that it can allow the sensitivity to improve by at least one order of magnitude under practical conditions.

g. ***Vapor Cell Size Effects:*** We examined the effect of the vapor cell on the radio frequency electric field measured at different positions inside the vapor cell [5]. The probe and coupling laser beams determined the position. The vapor cell was scanned so the lasers probed different sections of the vapor cell. We found that the if the vapor cell was ~10 times smaller than the wavelength of the radiation that the radio frequency electric field was uniform across the extent of the vapor cell to the level of the signal to noise, ~1%. The primary effect of the vapor cell was to setup a Fabry-Perot cavity for the radio frequency radiation. Cells with both sharp and rounded edges were investigated.

h. ***Atom-Surface Interaction Effects:*** In ref. [14], we explored the affect of adsorbates on Rydberg atoms held < 1mm away from a single crystal quartz surface. The adsorbates were Rb as were the Rydberg atoms. This work used the EIT method to detect constant electric fields from the adsorbates above the surface of the quartz and uncovered an interesting effect where slow electrons are captured in surface states on the quartz due to their image potential in the dielectric and the Rb doping of the surface. The Rb doping causes the vacuum level for the electrons outside the surface to shift into the band gap of the quartz. This induces negative electron affinity at the surface resulting in a repulsive wall for the electrons at the quartz-vacuum interface. The electrons float above the surface and cancel the field from the Rb adsorbates similar to the physics that can happen on the surface of superfluid helium. Effects like these will happen in small vapor cells. There is already some evidence for this effect occurring in vapor cells as presented in ref. [4].

III. Conclusion: During the course of this project, we invented the field of Rydberg atom-based radio frequency electric field sensing. There are many research groups now around the world as well as government labs like the Army Research Lab and NIST now participating in the field. In addition, there are at least four companies, including Honeywell, interested in the commercialization of this technology for various applications. By any measure, we can claim that the project was a great success.

During the QUASAR program, we demonstrated a sensitivity of 3 $\mu V\ cm^{-1}\ Hz^{-1/2}$ with an accuracy of ~1% for detection of radio frequency electric fields using our Rydberg atom-based method. The measurement is self-calibrated so it is able to make absolute measurements of the radio frequency electric fields. The sensor head is dielectric so it only minimally perturbs the radio frequency electric field. We investigated the extent of the perturbation caused by the vapor cell and were able to set out design principles to minimize the effect of the vapor cell on the measurements. At this point, we set the sensitivity limit which is determined by photon shot noise on the probe laser detector. We demonstrated vector detection and sub-wavelength imaging. Various read-out methods were explored. A formalism for setting the physical detection limits was developed and reported. The projection noise limited sensitivity was determined to be ~pV cm^{-1} $Hz^{-1/2}$.

IV. Bibliography:

[1] J. A. Sedlacek, A. Schwettmann, H. Kübler, R. Löw, T. Pfau, and J. P. Shaffer, Nature Physics 8, 819 (2012).

[2] H. Fan, S. Kumar, J. Sedlacek, H. Kübler, S. Karimkashi, and J. P. Shaffer, Journal of Physics B 48, 202001 (2015).

[3] C. Holloway, J. Gordon, S. Jefferts, A. Schwarzkopf, D. Anderson, S. Miller, N. Thaicharoen, and G. Raithel, IEEE Transactions on Antennas and Propagation 61, 6169 (2014).

[4] H. Kübler, J. Shaffer, T. Baluktsian, R. Löw, and T. Pfau, Nature Photonics 4, 112 (2010).

[5] H. Fan, S. Kumar, J. Sheng, J. P. Shaffer, C. L. Holloway, and J. A. Gordon, Physical Review Applied 4, 044015 (2015).

[6] H. Fan, S. Kumar, R. Daschner, H. Kübler, and J. Shaffer, Optics Letters 39, 3030 (2014).

[7] J. A. Gordon, C. L. Holloway, A. Schwarzkopf, D. A. Anderson, S. Miller, N. Thaicharoen, and G. Raithel, Applied Physics Letters 105, 024104 (2014).

[8] C. Wade, N. Sĭbalić, N. de Melo, J. Kondo, C. Adams, and K. Weatherill, arXiv:1603.07107 [physics.atom-ph].

[9] J. Sedlacek, A. Schwettmann, H. Kübler, and J. Shaffer, Physical Review Letters 111, 063001 (2013).

[10] T. F. Gallagher, Rydberg atoms, Vol. 3 (Cambridge University Press, 2005).

[11] S. Kumar, H. Fan, J. Sheng and J.P. Shaffer, Scientific Reports 7, 42981 (2017).

[12] S. Kumar, H. Fan, H. Kübler, A. Jozani, and J.P. Shaffer, Optics Express 25, 8625 (2017).

[13] J. P. Shaffer and L.G. Marcassa, Advances in Atomic, Molecular and Optical Physics, Advances in Atomic, Molecular and Optical Physics 63, 47 (2014).

[14] J.A. Sedelacek, E. Kim, S. T. Rittenhouse, P.F. Weck, H. Sadeghpour and J.P. Shaffer, Physical Review Letters 116, 133201 (2016).

V. Appendix I: List of Papers and Presentations

a. Papers

"FPGA-based locking circuit for external cavity diode laser frequency stabilization" Arne Schwettmann, Jonathon Sedlacek, and James Shaffer, Reviews of Scientific Instruments, 82, 103103 (2011).

"Quantum Assisted Electrometry using Bright Atomic Resonances," J. Sedlacek, A. Schwettmann, H. Kubler, R. Low, T. Pfau, and J.P. Shaffer, Nature Physics 8, 819 (2012).

"Fabrication and characterization of an electrically contacted vapor cell," R. Ritter, R. Daschner, H. Kübler, N. Frühauf, E. Kurz, R. Löw, T. Pfau. Optics Letters 37, 2271 (2012).

"Atom Based Vector Microwave Electrometry Using Rubidium Rydberg Atoms in a Vapor Cell," J. Sedlacek, A. Schwettmann, H. Kuebler and J.P. Shaffer, Physical Review Letters 111, 063001 (2013).

"Sub-wavelength microwave electric field imaging using Rydberg atoms inside atomic vapor cells," H. Fan, S. Kumar, H. Kubler, R. Daschner and J.P. Shaffer, Optics Letters 39, 3030 (2014).

"Interactions in Ultracold Rydberg Gases," J. P. Shaffer and L.G. Marcassa, Advances in Atomic, Molecular and Optical Physics (invited), Advances in Atomic, Molecular and Optical Physics 63, 47 (2014).

"Strongly correlated growth of Rydberg aggregates in a vapor cell," A. Urvoy, F. Ripka, I. Lesanovsky, D. Booth, J.P. Shaffer, T. Pfau and R. Low, Physical Review Letters 115, 203002 (2015) (editor highlight).

"Rydberg atom-based electric field sensing from radio to terahertz frequencies," H.Q. Fan, S. Kumar, H. Kubler, S. Karimkashi and J.P. Shaffer, Journal of Physics B 48, 202001 (2015) (invited Topical Review) (2015 Journal of Physics B highlighted article-2187 downloads).

"Effects of Vapor Cell Size on Rydberg Atom Electrometry," H.Q. Fan, S. Kumar, C. Holloway, J. Gordon and J.P. Shaffer, Physical Review Applied 4, 044015 (2015).

"Neutralization of Surface Adsorbate Electric Fields of Rubidium by Slow Electron Attachment," J.A. Sedelacek, E. Kim, S. T. Rittenhouse, P.F. Weck, H. Sadeghpour and J.P. Shaffer, Physical Review Letters 116, 133201 (2016).

"Atom-based RF Electric Field Measurements: An Initial Investigation of the Measurement Uncertainties," C. L. Holloway, J. A. Gordon, M. T. Simons, H. Fan, S. Kumar, J. P. Shaffer, D. A Anderson, A. Schwarzkopf, S. A. Miller, N. Thaicharoen and G. Raithel, Electromagnetic Compatibility (EMC), 2015 IEEE International Symposium on, 467 (2015).

"Microwave Electrometry using Rydberg Atomic Prism via Electromagnetically Induced Transparency," H.Q. Fan, S. Kumar, H. Kubler, and J.P. Shaffer, Journal of Physics B (Special Issue on Rydberg Atom Physics) 49, 104004 (2016).

"Surface Phonon-Polariton Dispersion Relation Analysis on Artificial Piezoelectric Superlattice Interfaces," Y. Chao, J. Sheng, J. Sedlacek and J.P. Shaffer, Physical Review B 93, 045419 (2016).

"Atom-Based Sensing of Weak Radio Frequency Electric Fields Using Homodyne Readout," S. Kumar, H. Fan, J. Sheng and J.P. Shaffer, Scientific Reports 7, 42981 (2017).

"Rydberg-atom Based Radio-Frequency Electrometry Using Frequency Modulation Spectroscopy in Room Temperature Vapor Cells," S. Kumar, H. Fan, H. Kübler, A. Jozani, and J.P. Shaffer, Optics Express 25, 8625 (2017).

b. Conference Publications:

"Generation of 480 nm CW Light for Rydberg Excitation of Rb," J. Sedlacek, A. Schwettmann, and J.P. Shaffer, DAMOP, Atlanta (2011).

“Probing RF Electric Fields with Rydberg Atoms,” A. Schwettmann, J. Sedlacek, C. Gentry, and J.P. Shaffer, DAMOP, Atlanta (2011).

“Coherent Rydberg Excitation in Thermal Microcells,” R. Low, R. Daschner, H. Kubler, B. Huber, T. Baluktsian, A. Koelle, J.P. Shaffer and T. Pfau, DAMOP, Atlanta (2011). (invited)

“A Rydberg Atom Electric Field Sensor,” J.P. Shaffer, DARPA Quasar and Orchid Meeting, San Diego, CA (2011). (invited)

“Probing RF Electric Fields with Rydberg Atoms,” A. Schwettmann, J. Sedlacek, C. Gentry, H. Kuebler and J.P. Shaffer, DARPA Quasar and Orchid Meeting, San Diego, CA (2011).

“A Rydberg Atom Electric Field Sensor,” J.P. Shaffer, DARPA Quantum Assisted Sensing-Fields, Cambridge, MA (2012). (invited)

“Quantum Assisted Sensing Using Rydberg Atom Electromagnetically Induced Transparency,” J. Sedlacek, H. Fan, A. Schwettmann, H. Kubler, T. Pfau, and J.P. Shaffer, DAMOP, Los Angeles, CA (

“Polarization Dependent Dark Resonances in Electromagnetically Induced Transparency with Rydberg Atoms,” J. Sedlacek, A. Schwettmann, H. Fan and J.P. Shaffer, DAMOP, Los Angeles, CA (2012).

“Quantum Assisted Sensing Using Rydberg Atom Electromagnetically Induced Transparency,” J.P. Shaffer, DARPA-Quasar Review, Santa Barbara, CA (2012).

“Vector Electrometry Using Rydberg Atom Electromagnetically Induced Transparency,” J. Sedlacek, H. Kubler, and J.P. Shaffer, DAMOP, Quebec City, Quebec, Canada (2013).

“Using Rydberg Atom Electromagnetically Induced Transparency for Microwave Electrometry Applications,” J. Sedlacek, H. Fan, R. Daschner, C. Ewel, H. Kubler and J.P. Shaffer, DAMOP, Quebec City, Quebec, Canada (2013).

“Quantum Assisted Sensing Using Rydberg Atom Electromagnetically Induced Transparency,” J.P. Shaffer, DARPA-Quasar Review, Santa Cruz, CA (2013).

“Quantum Assisted Sensing Using Rydberg Atom Electromagnetically Induced Transparency,” J.P. Shaffer, DARPA-Quasar Review, Long Beach, CA (2014).

"Quantum Assisted Electrometry using Electromagnetically Induced Transparency with Rydberg Atoms in a Vapor Cell," H.Q. Fan, S. Kumar, R. Daschner, H. Kubler, J. Sedlacek and J.P. Shaffer, DAMOP, Madison WI (2014).

"Sub-wavelength Microwave Electric Field Imaging using Rydberg Atoms," H.Q. Fan, S. Kumar, R. Daschner, H. Kubler, and J.P. Shaffer, DAMOP, Madison WI (2014).

"Probing Atom Surface Interactions Using Rb Rydberg Atoms," J. Sedlacek, H. Kubler, C. Ewel and J.P. Shaffer, DAMOP, Madison WI (2014).

“Quantum Assisted Sensing Using Rydberg Atom Electromagnetically Induced Transparency,” J.P. Shaffer, DARPA-Quasar Review, Boulder, CO (2014).

“Using Rubidium Rydberg Atoms to Probe Atom-Surface Interactions,” J. Sedlacek and J.P Shaffer, 2nd International Conference on Rydberg Atom Physics, Recife, Brazil (2014).

“Coherent Control of Strongly Interacting Rydberg Gases in Thermal Vapor Cells,” H. Kubler, R. Low, J.P. Shaffer and T. Pfau, 2nd International Conference on Rydberg Atom Physics, Recife, Brazil (2014). (invited)

“Cs Trilobite Molecules and Rydberg Atom Interactions,” D. Booth, J. Yang and J.P. Shaffer, 2nd International Conference on Rydberg Atom Physics, Recife, Brazil (2014).

“Production of a 2-D Electron Gas Using Rydberg Atoms and Surface Adsorbates,” J.P. Shaffer, B2 conference on Quantum Hybrid Systems, Tucson, AZ (2015). (invited)

“Quantum Assisted Sensing Using Rydberg Atom Electrometry,” J.P. Shaffer, DARPA-QUASAR Review, Boston, MA (2015).

“Atom-surface Studies with Rb Rydberg Atoms,” Y. Chao, J. Sheng, J. Sedlacek and J.P. Shaffer, DAMOP, Columbus, OH (2015).

“Homodyne Microwave Electric Field Measurements Using Cs Rydberg Atoms in Vapor Cells,” H. Fan, S. Kumar and J.P. Shaffer, DAMOP, Columbus, OH (2015).

“Neutralization of Rb Surface Adsorbate Electric Fields by Slow Electron Attachment,” J. Sedlacek, G. Chao and J.P. Shaffer, DAMOP, Columbus, OH (2015).

“Quantum Assisted Sensing Using Rydberg Atom Electrometry,” J.P. Shaffer, DARPA-QUASAR Review, Santa Barbara, CA (2015).

“Electric field cancellation on quartz by Rb adsorbate-induced negative electron affinity,” J.P. Shaffer, DAMOP, Providence, RI (2016). (invited)

“Electromagnetically induced transparency with Rydberg atoms inside a high-finesse optical cavity,” J. Sheng, S. Kumar, J. Sedlacek, Y. Chao, H. Fan and J.P. Shaffer, DAMOP, Providence, RI (2016).

“Radio-frequency Electrometry Using Rydberg Atoms in Vapor Cells: Towards the Shot Noise Limit,” S. Kumar, H. Fan, A. Jahangiri, H. Kubler, and J.P. Shaffer, DAMOP, Providence, RI (2016).

“Electric field cancellation on quartz by Rb adsorbate-induced negative electron affinity,” J.P. Shaffer, Correlation and Order in Rydberg Gases, Lorentz Center, Leiden, Netherlands (2016). (invited)

“Electric field cancellation on quartz by Rb adsorbate-induced negative electron affinity,” J.P. Shaffer, LAOP, Medellin, Colombia (2016). (invited)

“Quantum Assisted Sensing Using Rydberg Atom Electrometry,” J.P. Shaffer, DARPA-QUASAR Review, Arlington, VA (2016).

“Microwave electric field measurement using frequency modulation spectroscopy in Rydberg atoms vapor cells,” S. Kumar, H. Fan, A. Jozani, H. Kübler, and J.P. Shaffer, The International Conference on Fiber Optics and Photonics (PHOTONICS 2016), Kanpur, India (2016).

“Weak microwave electric field measurement using Rydberg atoms in vapor cells,” S. Kumar, H. Fan, A. Jozani, H. Kübler, and J.P. Shaffer, DAE-BRNS National Laser Symposium (NLS-25) KIIT University, Bhubaneswar, India (2016).

“Rb adsorbate-induced negative electron affinity on quartz,” J. A. Sedlacek, E. Kim, S. T. Rittenhouse, P. F. Weck, H. R. Sadeghpour, and J. P. Shaffer, ICPEAC, Queensland, Australia (2017).

“Sensitivity limits of Rydberg atom-based radio frequency electric field sensing,” A. Jahangiri, S. Kumar, H. Kubler, H. Fan and J.P. Shaffer, DAMOP, Sacramento, CA (2017).

“Photon shot noise limited radio frequency electric field sensing using Rydberg Aatoms in vapor cells,” S. Kumar, A. Jahangiri, H. Fan, H. Kubler and J.P. Shaffer, DAMOP, Sacramento, CA (2017).

“Quantum signal transduction using Rydberg atoms,” Y. Chao and J.P. Shaffer, Second International Conference on Rydberg Atoms and Molecules, Taiyuan, China (2017). (invited)

c. Colloquia

“Sensing Electric Fields with Rydberg Atoms,” J.P. Shaffer, University of Stuttgart, Germany (2012).

“Sensing Electric Fields with Rydberg Atoms,” J.P. Shaffer, Oklahoma State University (2012).

“Quantum Assisted Sensing Using Rydberg Atom Electromagnetically Induced Transparency,” J.P. Shaffer, State Key Laboratory of Magnetic Resonance and Atomic and Molecular Physics, Wuhan Institute of Physics and Mathematics, Chinese Academy of Sciences, Wuhan 430071, China (2013).

“Electric field cancellation on quartz by Rb Adsorbate-Induced Negative Electron Affinity,” University of Michigan, Ann Arbor (2016).

“Electric Field Cancellation on Quartz by Rb Adsorbate-Induced Negative Electron Affinity and Rydberg Atom Surface Interactions” University of Sao Paulo, Sao Carlos, Brazil (2016).

“Electric Field Cancellation on Quartz by Rb Adsorbate-Induced Negative Electron Affinity and Rydberg Atom Surface Interactions” University of Sao Paulo, Sao Paulo, Brazil (2016).

“Electric field cancellation on quartz by Rb adsorbate-induced negative electron affinity,” J.P. Shaffer, University of Stuttgart (2016).

“A Rydberg atom-based sensor for microwave electric fields,” Honeywell, Plymouth, MN (2017).

d. Summer Schools

“The School on Interaction of Light with Cold Atoms,” in Sao Paulo, Brazil (2017) sponsored by the International Centre for Theoretical Physics – South American Institute for Fundamental Research (http://www.ictp-saifr.org/?page_id=13276). (invited)