REPORT DOCUMENTATION PAGE

Form Approved OMB NO. 0704-0188

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From - To)
22-10-2018	Final Report	1-Sep-2011 - 28-Feb-2017

4. TITLE AND SUBTITLE
Final Report: Atom-Photon-Electro-Mechanical Interfaces for Quantum Force and Field Measurements

5a. CONTRACT NUMBER
W911NF-11-1-0235

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
0D10BM

6. AUTHORS

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES
University of Copenhagen
Kobenhavns Universitet
Norregade 10

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)
60346-PH-DRP.18

12. DISTRIBUTION AVAILIBILITY STATEMENT
Approved for public release; distribution is 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

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Eugene Polzik
UU	UU	UU	UU		19b. TELEPHONE NUMBER 452-338-2045

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

RPPR Final Report
as of 25-Jan-2019

Agency Code:

Proposal Number: 60346PHDRP **Agreement Number: W911NF-11-1-0235**

INVESTIGATOR(S):

Name: Eugene Polzik
Email: polzik@nbi.dk
Phone Number: 45233820450000
Principal: Y

Organization: **University of Copenhagen**
Address: Kobenhavns Universitet, Copenhagen, 1165
Country: DNK

DUNS Number: 310861591 EIN:
Report Date: 28-May-2016 Date Received: 22-Oct-2018
Final Report for Period Beginning 01-Sep-2011 and Ending 28-Feb-2017
Title: Atom-Photon-Electro-Mechanical Interfaces for Quantum Force and Field Measurements
Begin Performance Period: 01-Sep-2011 **End Performance Period:** 28-Feb-2018
Report Term: 0-Other
Submitted By: Eugene Polzik Email: polzik@nbi.dk
Phone: (452) 338-20450000
Distribution Statement: 1-Approved for public release; distribution is unlimited.

STEM Degrees: 20 **STEM Participants:** 16

Major Goals: The proposal goes beyond the existing state-of-the-art in two main thrusts of the call:
- Developing atomic magnetic field sensors operating beyond the standard quantum limit (SQL) and reaching the record sensitivity
- Constructing hybrid quantum sensors of force and electro-magnetic field based on strong coupling of nano-mechanical systems and electronic inductor-capacitor resonant circuits (LC circuits) to light and atomic spins which allows for laser cooling and shot noise limited optical readout of these disparate systems, and
- Entangling atomic, optical, nano-mechanical and electronic systems in various combinations to operate beyond the SQL.

The various systems used here, such as atomic spin ensembles, nano-mechanical oscillators, LC circuits and light, can be all described by a unifying formalism of harmonic oscillators, and their interactions are similarly described by several universal Hamiltonians, such as a swap, a parametric and a quantum non-demolition Hamiltonian. These unifying features, once noticed, allow for efficient transfer of methods for quantum states engineering and control between different realizations. One of the key consequences of such control for quantum sensing is the ability to cool mechanical and electrical sensors down to the SQL using coupling to light and atomic spin ensembles, two systems with zero effective temperature.

We will develop a transduction system for coupling the mechanical motion of a nanomembrane, which will be coupled to an optical cavity, to allow it co couple also to an electrical system. This transduction will allow for direct conversion between radio frequency photons and optical photons in the cavity; furthermore, it enables optical cooling of the electrical system, and can provide similar bandwidth-sensitivity tradeoffs as those seen for pure force/acceleration sensing. Further improvements, such as the use of high temperature superconducting inductor/capacitor elements, will in principle allow for the conversion and detection of single radio frequency photons, a tour-de-force in electrical detection. This hybrid system will also enable to couple between more conventional magnetometers, such as atomic magnetometers as described below, and the electrical system, and naturally leads to the advantages of atomic magnetometers such as back-action evading measurement, for pick-up coil-based magnetic sensing.

Finally, we will extend the state of the art in atomic magnetometry for sensing mm to micrometer scale magnetic fields by using three different techniques: atomic microcells of Caesium, entangling distant atomic cells for improved sensitivity, and trapping cold atoms for magnetometry using sub-micrometer scale traps. This effort will culminate in the demonstration of applications of the quantum magnetometer to detection of magnetic fields of biological objects, such as dendrites in neurons.

Accomplishments: Our work on quantum-limited magnetometry culminated in the first detection of action potentials from an animal nerve using an optical atomic magnetometer. Using an optimal design we are able to

achieve the sensitivity dominated by the quantum shot noise of light and quantum projection noise of atomic spins. Such sensitivity allows us to measure the nerve impulse with a miniature room-temperature sensor which is a critical advantage for biomedical applications. Positioning the sensor at a distance of a few millimeters from the nerve, corresponding to the distance between the skin and nerves in biological studies, we detect the magnetic field generated by an action potential of a frog sciatic nerve. From the magnetic field measurements we determine the activity of the nerve and the temporal shape of the nerve impulse. This work opens new ways towards implementing optical magnetometers as practical devices for medical diagnostics.
A followup work presently accepted for publication reports on a highly sensitive miniature optically pumped magnetometer based on cesium atomic vapor kept in a paraffin-coated glass container. The magnetometer is optimized for detection of biological signals and has high temporal and spatial resolution. It is operated at room- or human body temperature and can be placed in contact with or at a mm-distance from a biological object. With this magnetometer, we detected the heartbeat of an isolated guinea-pig heart, which is an animal widely used in biomedical studies. In our recordings of the magnetocardiogram, we can in real-time observe the P-wave, QRS-complex and T wave associated with the cardiac cycle. We also demonstrate that our device is capable of measuring the cardiac electrographic intervals, such as the RR- and QT-interval, and detecting drug-induced prolongation of the QT-interval, which is important for medical diagnostics.

Opto-mechanical transducer for detection of radio waves reported with the load Johnson noise limited sensitivity of 800pV/SqrtHz and intrinsic noise of less than 100 pV/SqrtHz. Theoretical studies led to the primary realization of a method of achieving strong, quantum nonlinear effects in optical mechanical systems by driving side-band resolved, weakly coupled systems close to instability. Quantum magnetometry with room temperature atoms in microcells with 2D spatial resolution of 300 microns is demonstrated. Cavity enhanced quantum nondemolition detection of magnetic field achieved with record sub-projection noise sensitivity of 250 femtoTesla/Hz(1/2) for this spatial resolution. The second platform for quantum magnetometry under development is a string of atoms, photon crystal, trapped around a nanofiber. We have demonstrated trapping of 2000 atoms localized to better than 200 nm in two dimensions. Minimally destructive optical probing of the trapped atoms has been demonstrated paving the road towards spin state measurements and magnetometry. Primary accelerometer improvements included realization of sub 100 ng/Hz(1/2) sensitivity over 10 kHz bandwidth from near DC, limited by laser frequency noise, with a 1 kHz bandwidth sensitivity near mechanical resonance approaching the 2 ng/Hz(1/2) thermally-limited sensitivity.

Finally, we have extended our work on sensing beyond the standard quantum limits towards measurement of motion of a mechanical oscillator. Quantum mechanics dictates that a continuous measurement of the position of an object imposes a random quantum back-action (QBA) perturbation on its momentum. This randomness translates with time into position uncertainty, thus leading to the well known uncertainty on the measurement of motion. As a consequence of this randomness, and in accordance with the Heisenberg uncertainty principle, the QBA puts a limitation—the so-called standard quantum limit—on the precision of sensing of position, velocity and acceleration. We show that QBA on a macroscopic mechanical oscillator can be evaded if the measurement of motion is conducted in the reference frame of an atomic spin oscillator. The collective quantum measurement on this hybrid system of two distant and disparate oscillators is performed with light. The mechanical oscillator is a vibrational ‘drum’ mode of a millimetre-sized dielectric membrane, and the spin oscillator is an atomic ensemble in a magnetic field. The spin oriented along the field corresponds to an energetically inverted spin population and realizes a negative effective-mass oscillator, while the opposite orientation corresponds to an oscillator with positive effective mass. The QBA is suppressed by −1.8 decibels in the negative-mass setting and enhanced by 2.4 decibels in the positive-mass case. This hybrid quantum system paves the way to entanglement generation and distant quantum communication between mechanical and spin systems and to sensing of force, motion and gravity beyond the standard quantum limit.
We have come up with an idea for improving the sensitivity of Gravitational Wave Detectors, such as LIGO, using our concept of measurement in the negative mass reference frame. This proposal is currently under experimental implementation at our laboratory.

RPPR Final Report
as of 25-Jan-2019

Training Opportunities: 10 PhD students have graduated during the course of this project.

Nir S. Kampel. Thesis defended in December 2012: Forward and backward scattering experiments in ultra-cold Rubidium atoms

Tolga Bagci. Thesis defended in February 2014: OPTO-ELECTROMECHANICAL DEVICES FOR LOW-NOISE DETECTION OF RADIO WAVES

Stefan Lund Christense. Thesis defended in August 2014: Generation of exotic quantum states of a cold atomic ensemble.

Heng Shen. Thesis defended in December 2014: Spin squeezing and entanglement with room temperature atoms for quantum sensing and communication.

Jean B. Beguin. Thesis defended in May 2015: A One-dimensional Quantum Interface Between a Few Atoms and Weak Light.

Heidi Lundgaard Sørensen. Thesis defended in December 2015: A waveguide platform for collective light-atom interaction

Andreas Naesby Rasmussen. Thesis defended in January 2016: Optomechanics with Semiconductor Nanomembranes

William H. P. Nielsen. Thesis defended in May 2016: Quantum Cavity Optomechanics with Phononic Bandgap Shielded Silicon Nitride Membrane

Michael Zugenmaier. Thesis defended in January 2018: Towards an on-demand single photon source based on room temperature vapor cell.

Christoffer Moller. Thesis defended in February 2018: Quantum Back-Action Evasion in a Hybrid Spin-Optomechanical System.

Results Dissemination: Results stemming from this project have been reported at more than 20 international conferences, including:
Gordon Conferences 2012, 2015, 2016, 2018, American Physical Society DAMOP meeting 2016, American Physical Society March Meeting 2017, International Conference on Quantum Communication and Measurement 2014, 2018.

Selected media coverage of the research results:
Phys.org/news/2017-07-smart-atomic-cloud-heisenberg-problem.html
Fysiker flytter kvantegrænser. magisterbladet.dk/magisterbladet/2014/112014/112014_p21
Physics World 2014: physicsworld.com/cws/article/news/2014/mar/05/tiny-membrane-converts-radio-waves-to-light
Scientific American 2014: scientificamerican.com/podcast/episode/laser-tuner-boosts-radio-reception-13-08-21/
videnskab.dk/miljo-naturvidenskab/danskere-opsnapper-ultrasvage-radiosignaler
Physics World 2013: http://physicsworld.com/cws/article/news/2013/jun/11/quantum-teleportation-done-between-distant-large-objects

Honors and Awards: Selected honors and awards received by the PI, Eugene Polzik:
- 2018 – European Research Council Advanced Grant award
- 2014 – Danish Academic Association (Magisterforening) Research Prize in Natural Sciences
- 2013 – selected as the Danish Research Result of the Year by Ingeniøren magazine

Protocol Activity Status:

Technology Transfer: • Optical detector and amplifier for rf-detection having a position dependent capacitor with a displaceable membrane. E.S.Polzik et al. US patent number 9.660.721 B2, Date of patent May 23, 2017.

RPPR Final Report
as of 25-Jan-2019

PARTICIPANTS:

Participant Type: Faculty
Participant: Juergen Appel
Person Months Worked: 15.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)
Participant: Kasper Jensen
Person Months Worked: 15.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

ARTICLES:

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Journal of Physics B: Atomic, Molecular and Optical Physics
Publication Identifier Type: DOI Publication Identifier: 10.1088/0953-4075/45/12/124021
Volume: 45 Issue: 12 First Page #: 124021
Date Submitted: Date Published:
Publication Location:
Article Title: Robust entanglement generation by reservoir engineering
Authors:
Keywords: entanglement, dissipation, quantum measurement
Abstract: Following a recent proposal (Muschik et al 2011, PRA 83, 052312), engineered dissipative processes have been used for the generation of stable entanglement between two macroscopic atomic ensembles at room temperature (Krauter et al, 2011 PRL 107, 080503). This experiment included the preparation of entangled states which are continuously availability during a time interval of one hour. Here, we present additional material, further-reaching data and an extension of the theory. In particular, we show how the combination of the entangling dissipative mechanism with measurements can give rise to a substantial improvement of the generated entanglement in the present of noise.
Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support:

RPPR Final Report
as of 25-Jan-2019

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Nature Physics
Publication Identifier Type: DOI Publication Identifier: 10.1038/nphys2196
Volume: 8 Issue: 2 First Page #: 168
Date Submitted: Date Published:
Publication Location:
Article Title: Optical cavity cooling of mechanical modes of a semiconductor nanomembrane
Authors:
Keywords: opto-mechanical cooling, semiconductors, nanomembrane
Abstract: Mechanical oscillators can be optically cooled using a technique known as optical-cavity back-action. Cooling of composite metal–semiconductor mirrors, dielectric mirrors and dielectric membranes has been demonstrated. Here we report cavity cooling of mechanical modes in a high-quality-factor and optically active semiconductor nanomembrane. The cooling is a result of electron–hole generation by cavity photons. Consequently, the cooling factor depends on the optical wavelength, varies drastically in the vicinity of the semiconductor bandgap, and follows the excitonic absorption behaviour. The resultant photo-induced rigidity is large and a mode temperature cooled from room temperature down to 4 K is realized with 50 micro┬W of light and a cavity finesse of just 10. Thermal stress due to non-radiative relaxation of the electron–hole pairs is the primary cause of the cooling.We also analyse an alternative cooling mechanism that is a result of electronic stress via the deformation potentia
Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support:

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Physical Review Letters
Publication Identifier Type: DOI Publication Identifier: 10.1103/PhysRevLett.107.273601
Volume: 107 Issue: 27 First Page #: 273601
Date Submitted: Date Published:
Publication Location:
Article Title: Laser Cooling and Optical Detection of Excitations in a LC Electrical Circuit
Authors:
Keywords: quantum coupling, radio-frequency, optical readout
Abstract: We explore a method for laser cooling and optical detection of excitations in a room temperature LC electrical circuit. Our approach uses a nanomechanical oscillator as a transducer between optical and electronic excitations. An experimentally feasible system with the oscillator capacitively coupled to the LC and at the same time interacting with light via an optomechanical force is shown to provide strong electromechanical coupling. Conditions for improved sensitivity and quantum limited readout of electrical signals with such an ‘‘optical loud speaker’’ are outlined.
Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support:

RPPR Final Report
as of 25-Jan-2019

Publication Type: Journal Article Peer Reviewed: N **Publication Status:** 5-Submitted
Journal: Annalen der Physik
Publication Identifier Type: Publication Identifier:
Volume: 0 Issue: 0 First Page #: 0
Date Submitted: Date Published:
Publication Location:
Article Title: “From membrane-in-the-middle to mirror-in-the-middle with a high-reflectivity sub-wavelength grating”
Authors:
Keywords: optomechanics, sub-wavelength grating
Abstract: We demonstrate a \membrane in the middle" optomechanical system using a silicon nitride membrane patterned as a subwavelength grating. The grating has a reectivity of over 99.8%, e♂ectively creating two sub-cavities, with free spectral ranges of 6 GHz, optically coupled via photon tunneling. Measurements of the transmission and reection spectra show an avoided crossing where the two sub-cavities simultaneously come into resonance, with a frequency splitting of 54 MHz. We derive expressions for the lineshapes of the symmetric and antisymmetric modes at the avoided crossing, and infer the grating reection, transmission, absorption, and scattering through comparison with the experimental data.
Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support:

"Nothing to report in the uploaded pdf (see accomplishments)"